Role of Microstructure on Fatigue Durability of Aluminum Aircraft Alloys

(ONR Contract No. N00014-91-C-0128)

ALCOA

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Contract Review Meeting
Office of Naval Research
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Outline

- Background
  - The problem (needs & technical gaps)
  - The opportunity (program objective)
- Fatigue quality assessment
  - Lessons learned (7050 thick plate)
  - Evaluation of 7050 thick plate derivatives
  - Hierarchy of controlling microstructure features
  - New and improved product opportunities
- Removing barriers to quality exploitation
- Program expectations/deliverables
- Microstructural characterization and related methodologies
- Modeling
  - Structural payoffs
  - Microstructure based life prediction
  - Probabilistic approach
  - Preliminary conclusions
- Future work suggestions

Situational challenge
DoD & U.S. aerospace industry

- Sustain global preeminence in time of budget reductions and downsizing
- Affordable systems that are safe, efficient to operate/maintain and last longer
- Do more with less
  - Better products/services in shorter time at less cost
  - Increase quality and performance without increasing resources
  - Capitalize on existing infrastructure and technologies

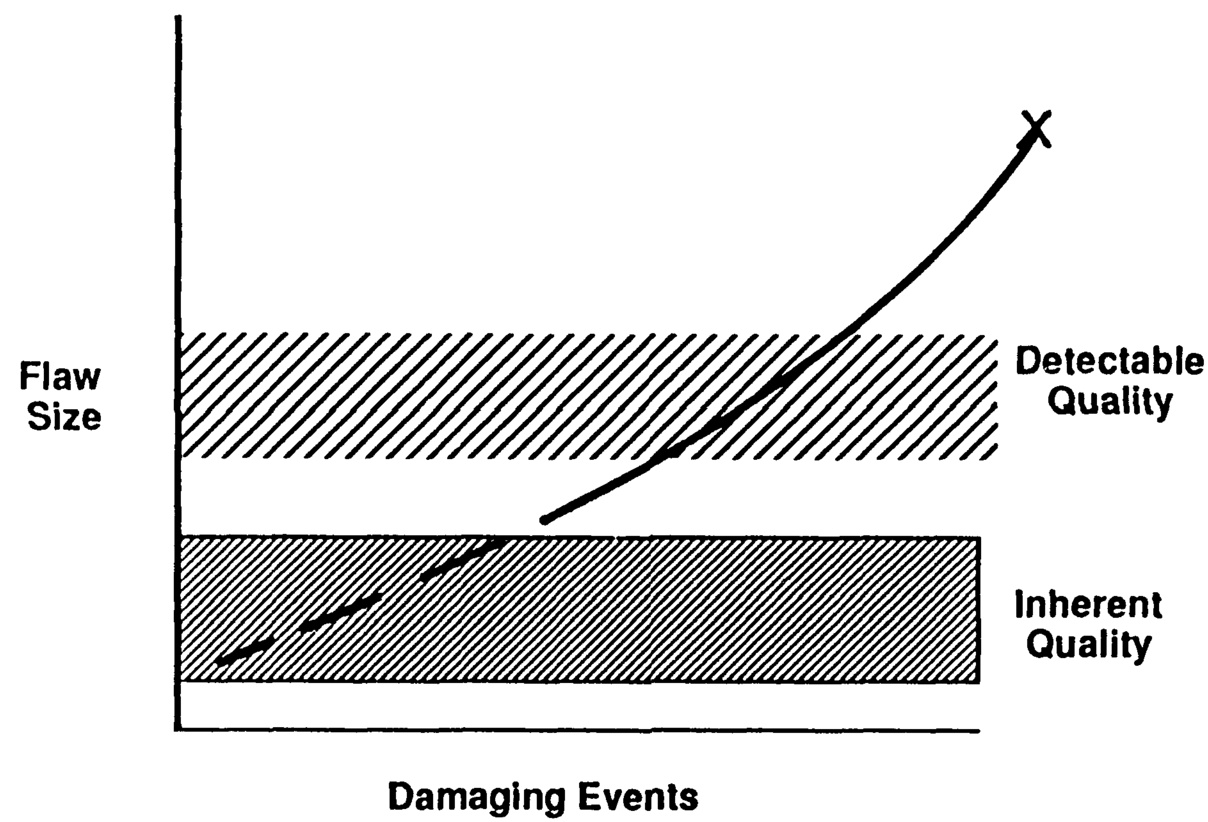
Providing a higher quality/performing product more rapidly and less expensively should be a goal whatever the enabling technology

Enabling Technology Gaps
Affordable Air Vehicle Structures

- Data, protocols and tools to
  - Optimize balance of performance with costs of acquisition and operation
  - Reduce time, complexity and cost of product development, design, modification, test and certification processes
  - Address R&M trade-offs up front; minimize in-service inspections and repairs
  - Assess risk of widespread cracking in aging fleet
- Procedures providing incentive for quality as it comes off the production line
  - Quantification of cost-performance benefit
  - Hard data to reform inefficient procurement practices
- Life enhancing products and procedures

System integrity begins with quality of the starting materials

Initial Quality Assessment



What is wanted?

Ultimate objective:

- Develop and exploit higher quality materials and manufacturing practices to save weight, extend life and reduce life-cycle costs

Program objective:

- Quantify benefit of improved quality materials; establish fatigue quality data base
- Provide enabling technology to develop and exploit higher quality/performing materials and manufacturing practices more rapidly and less expensively
- <u>Affect change</u> to incorporate microstructure into life assessment methodologies
- Tie to technology development cycle; show readiness for concept scale up:
  - Life assessment methodology
  - New product(s)
  - Replacement parts

Technology Development Cycle

Technology Development Cycle	Status (Remarks)
1. Search for ideas	
- Statement of ideas	√
- Customer needs	√
- Opportunities	√
- Ideas advantages	√
* ***Idea screen***	√
2. Develop concept	
- Comprehensive statement of concept	√
- Strategic fit with DoD/Alcoa objectives	√
* ***Concept review***	√
3. Evaluate concept	
- Feasibility demonstration for critical elements	√
- Success elements	√
- Customer feedback on the concept	(√)
* ***Project proposal review***	(√)
4. Demonstrate full concept	
- Produce prototype product/processes	
- Reassess all issues and identify all	
- Unresolved project risks	
* ***Prototype marketability review***	
5. Verify large scale capacity	
- Produce and evaluate prototype	
- Finalize product characteristics & specifications	
* ***Producibility and commercialization review***	
6. Implement in full production	
- Purchase and install equipment	
- Train production teams	
* ***Final project review***	
7. Continuous improvement	
- Customer service	
- Value tracking	

Need multifunctional information network
End-user, Customer, Supplier
R&D, Engineering, Manufacturing, Procurement, Quality control

Opportunity
Fatigue Quality Improvement

- Initiation and small crack growth comprise the major life fraction of most cyclically loaded components
- Lab scale testing has shown potential for dramatic fatigue life increase with metal quality improvement
- Metallurgical quality features most influential to formation and growth of small cracks are pores, particles and grain structure (in that order)
- Other performance attributes enhanced by metal quality increase
- Thick parts have greatest improvement potential

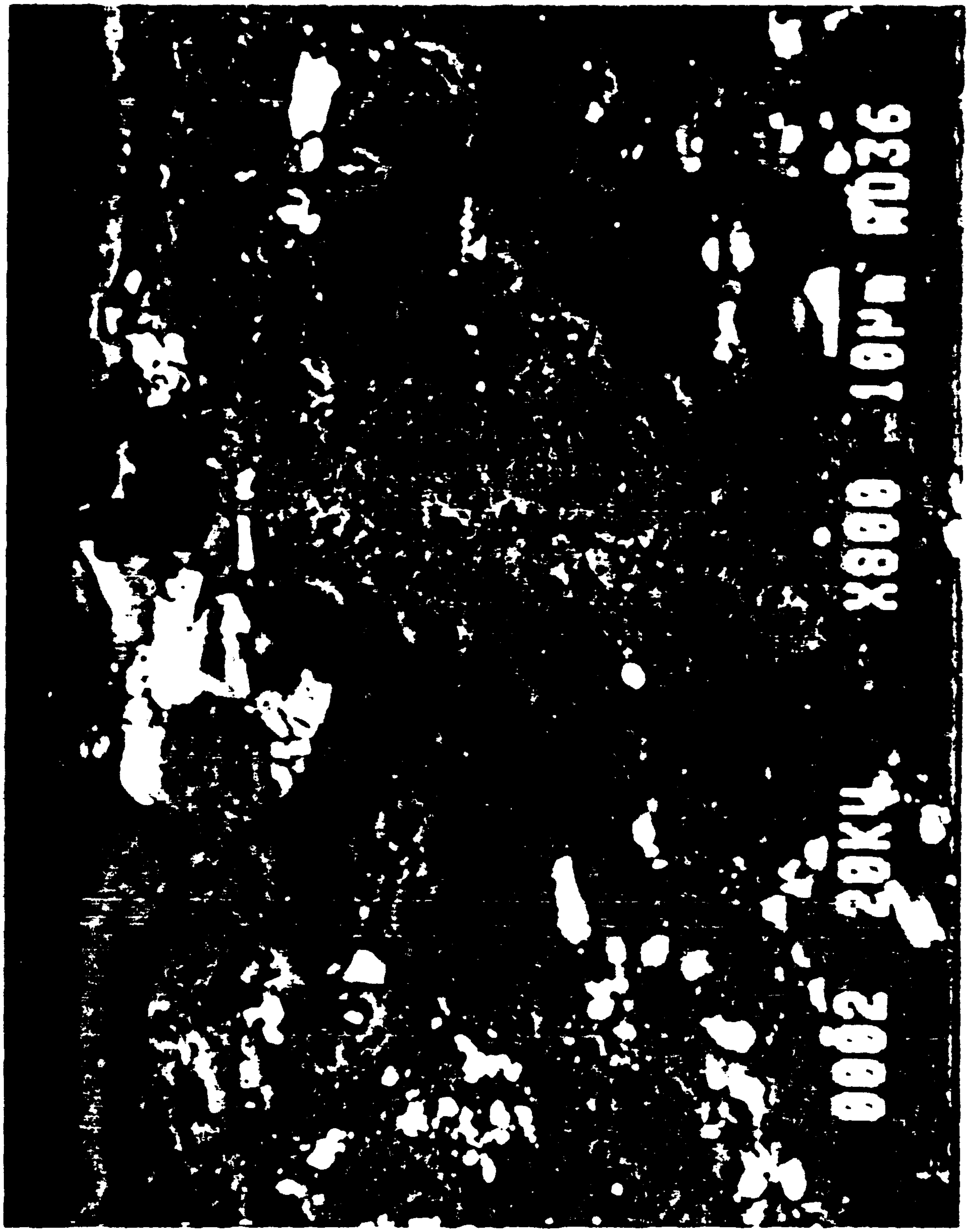
Quality oriented modifications of existing metallic products offer an affordable alternative to exotic (unproven) new technologies

Why Thick Product?

Focus is role of microstructural inhomogeneities as they affect fatigue durability of heavy section airframe parts

- Pores/particles implicated in investigations of aging aircraft problem parts
- Thick parts are internal to the structure, making in-service inspections more difficult
- Internal structure is less prone to traffic damage than external structure (i.e., favors crack nucleation from features intrinsic to the material)
- Fatigue initiating microstructure features are too small for reliable inspection
- Thick structure is expensive to repair or replace

Increasing thick structure durability provides weight and operator cost saving opportunities



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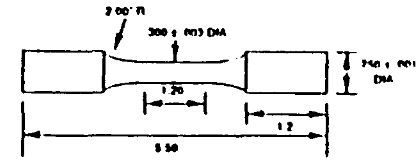
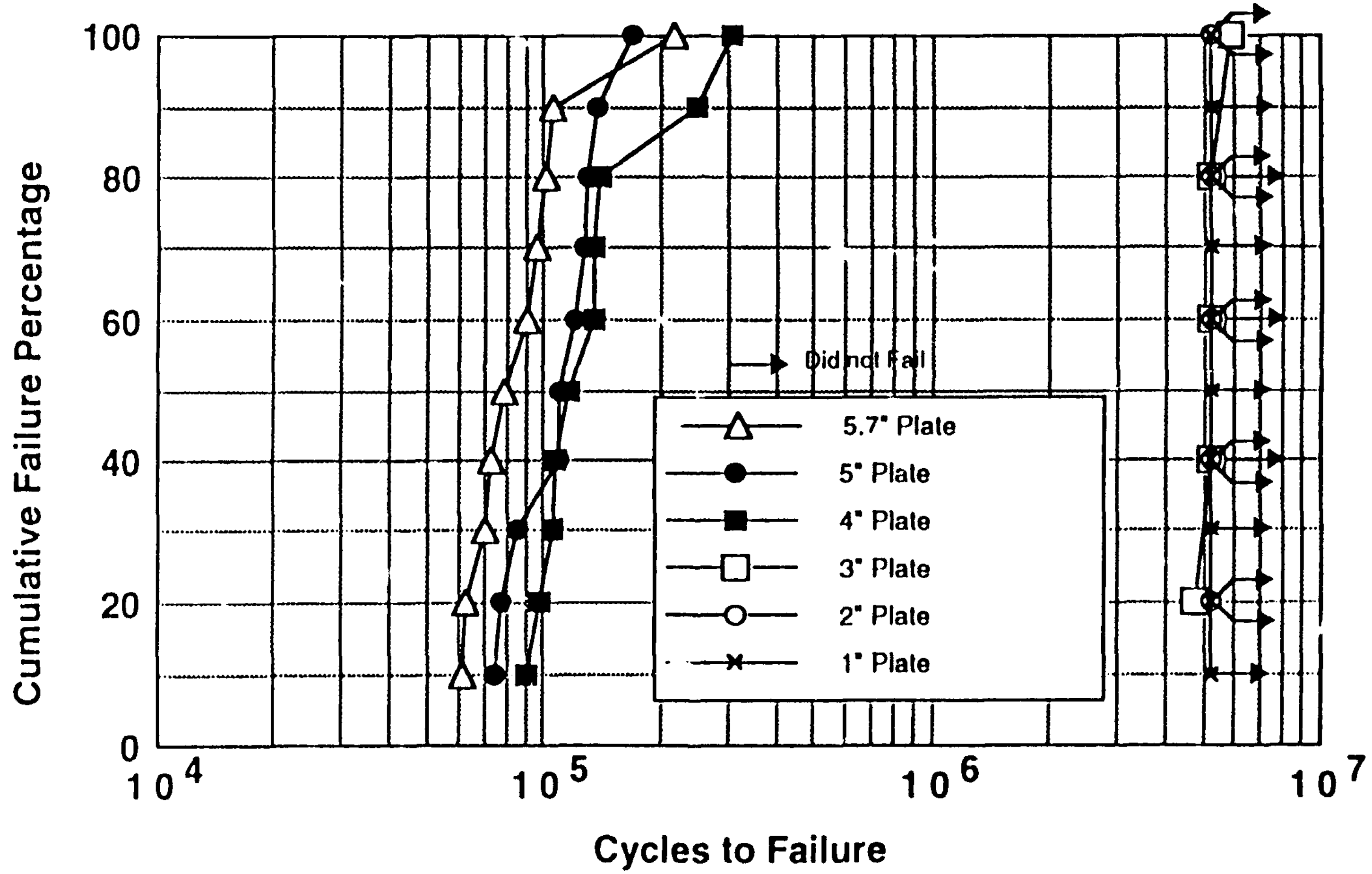
7050-T7451 Plate (1" to 5.7" thick)
Cumulative Fatigue Failure Distributions
Maximum Stress 40 ksi, R = +0.1
Long Transverse, T/2 Test Location





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Lessons Learned

7050 Thick Plate Fatigue Investigations (1982-present)

- Appreciable gains in manufacturing productivity and fatigue lifetime capability realized by installing process controls to limit severity of pore and particle populations in material manufacture
    - Dramatic drop in number of ultrasonic and die penetrant rejections; reduced scrap
    - Statistical fatigue advantage confirmed under variety of test conditions
    - Hierarchy of failure mechanisms identified for smooth and notched (open hole) specimen tests
    - Fatigue quality assurance test commercially implemented
    - Increased customer satisfaction
- Probabilistic fatigue durability framework captures performance advantage of improved metal quality, where more conventional fatigue design practices do not
    - Hypothetical performance and cost saving scenarios developed

Lessons Learned (continued)

7050 Thick Plate Fatigue Investigations (1982-present)

- Defined next generation 7050 thick product (HFL Plate)
  - Essential process improvements identified; concept validated with plant produced material
  - Alternate material processing route identified to reduce plant fabrication cost (trial in progress)
- Change in material specification and procurement practices will be necessary to exploit higher quality materials
- Technology transferred to other Alcoa alloy/process developments. Enhanced product capabilities include:
  - Strength
  - Fracture toughness
  - Fatigue crack growth (high ΔK and spectrum)
  - Short transverse ductility
  - Capacity for mechanical work (e.g., cold working of holes)
  - Applicability extended to thin plate and forgings

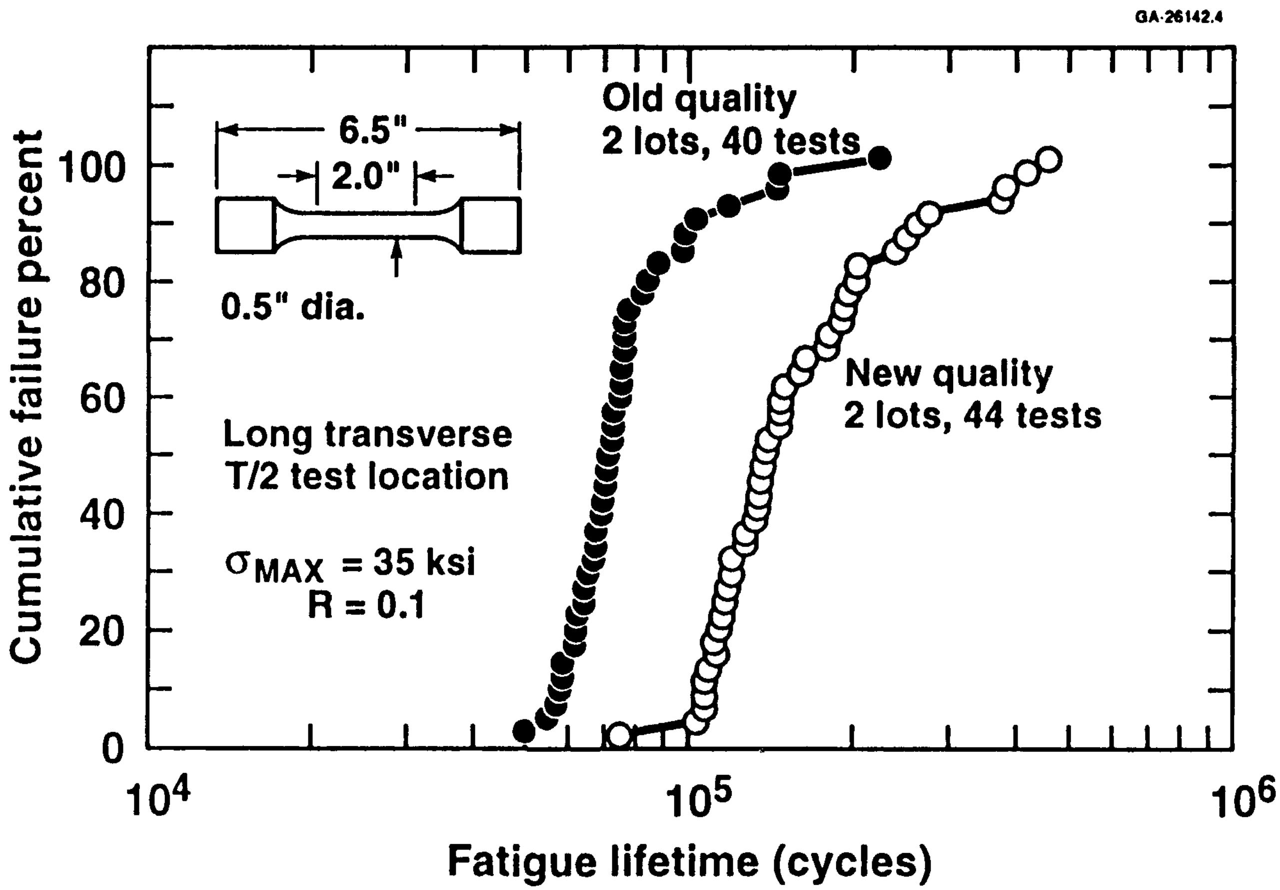
Documentation of historical data and lessons learned are key program deliverables

7050 Materials

Key microstructural features of Alcoa materials made available to the ONR for this study

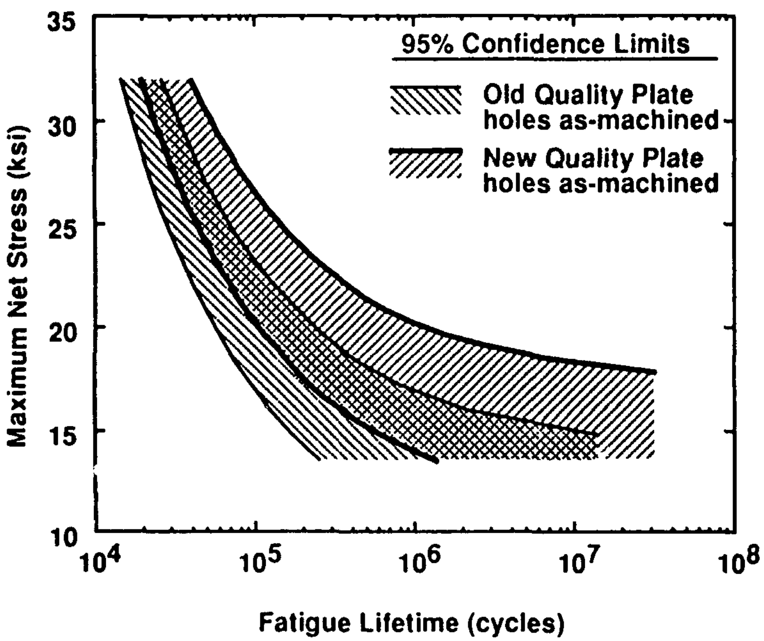
Material	Product Thickness (in.)	Key Microstructural Features
Old Quality Plate	5.7	Coarse Microporosity
New Quality Plate	5.7	Microorosity
Low Porosity Plate	6.0	Small Microporosity, Constituent Particles
Thin Plate	1.0	Refined Grain Size, Constituent Particles

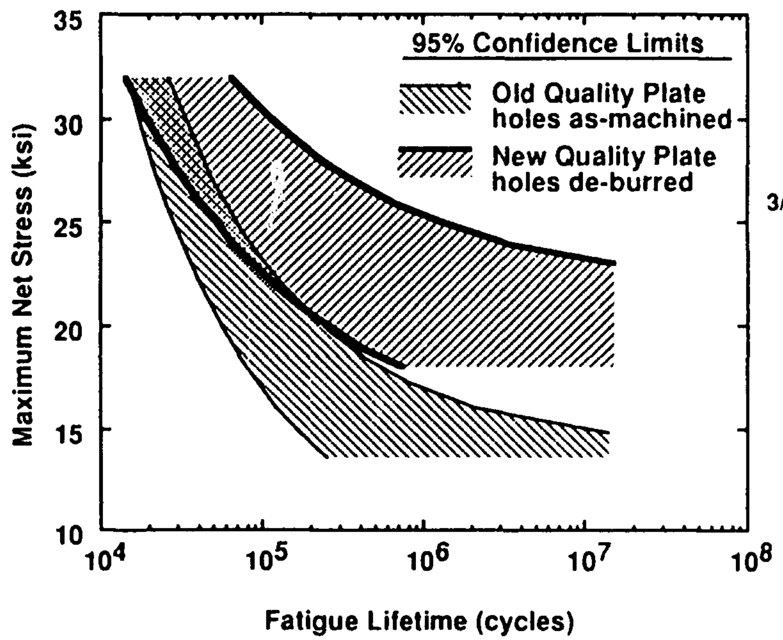
Cumulative Fatigue Failure Distributions
Old and New Quality 7050-T7451
5.7 in. Thick Plate

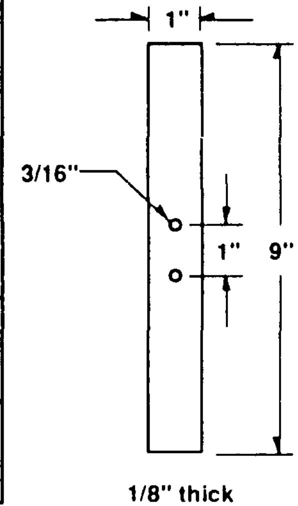


Effect of Hole Condition on Fatigue Quality Improvement

Stress vs. life (S/N) open hole fatigue data for 7050 old and new quality thick plate, tested at R=0.1, frequency = 30 Hz, lab air, LT orientation, T/2 location



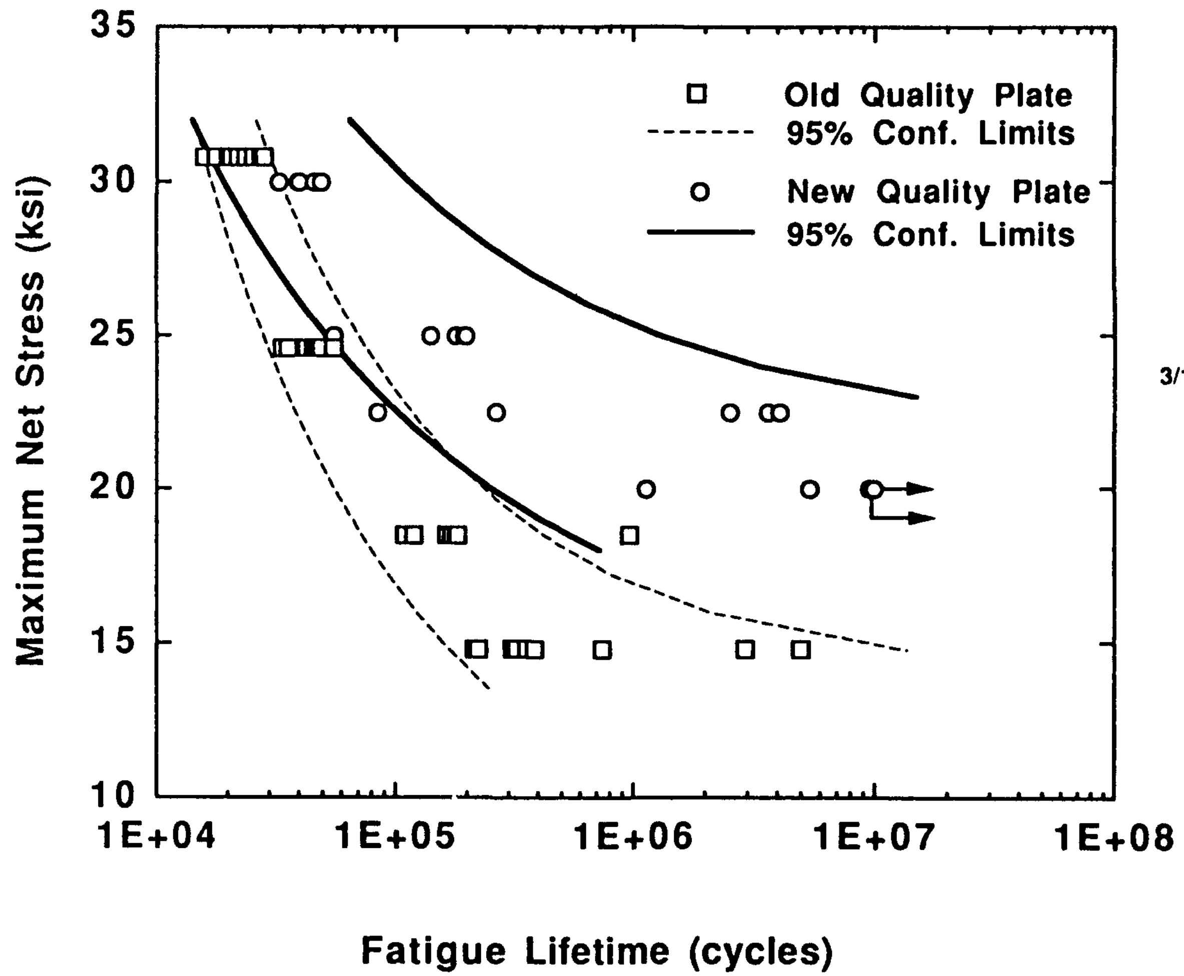


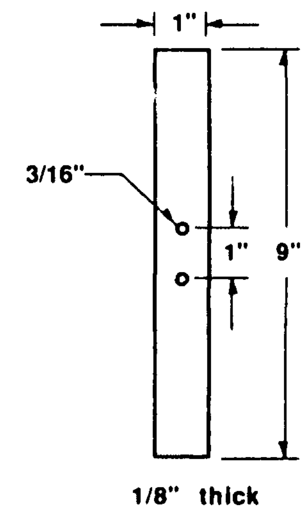


Material	Hole Condition	Initiation Mechanism
Old Quality	as-machined	coarse microporosity
New Quality	as-machined	hole burrs
New Quality	de-burred	microporosity

Open Hole Fatigue: Old and New Quality Thick Plate

Stress vs. life (S/N) open hole fatigue data for 7050 old and new quality plate, tested at R=0.1, frequency = 30 Hz, Lab air, LT orientation





7050 Thick Plate Fatigue Strength Increase With Quality Improvement

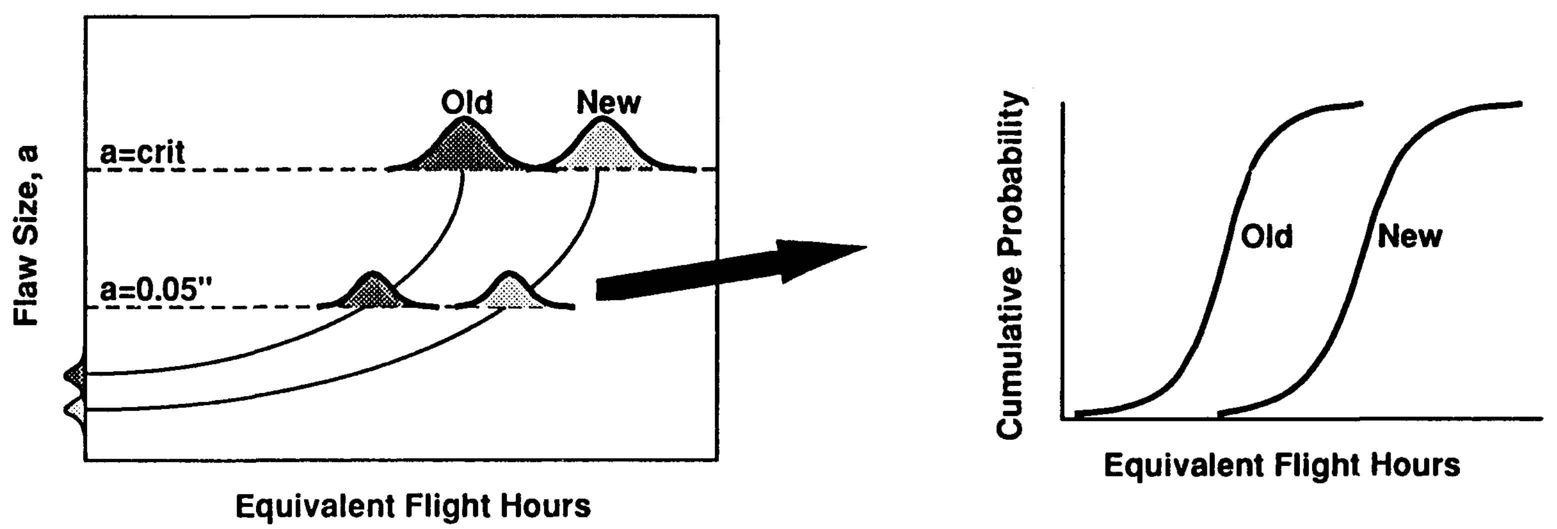
Calculated stress corresponding to specified lifetime for open hole fatigue tests of new and old quality thick plate

	Maximum Net Stress (ksi)*			
	10^5 Cyclic Lifetime		Infinite Lifetime	
Metal Quality	Mean	95% Lower Conf. Limit	Mean	95% Lower Conf. Limit
Old Quality	20.1	16.9	10.8	7.7
New Quality	26.5	22.6	17.7	13.9
% Change	32%	34%	64%	81%

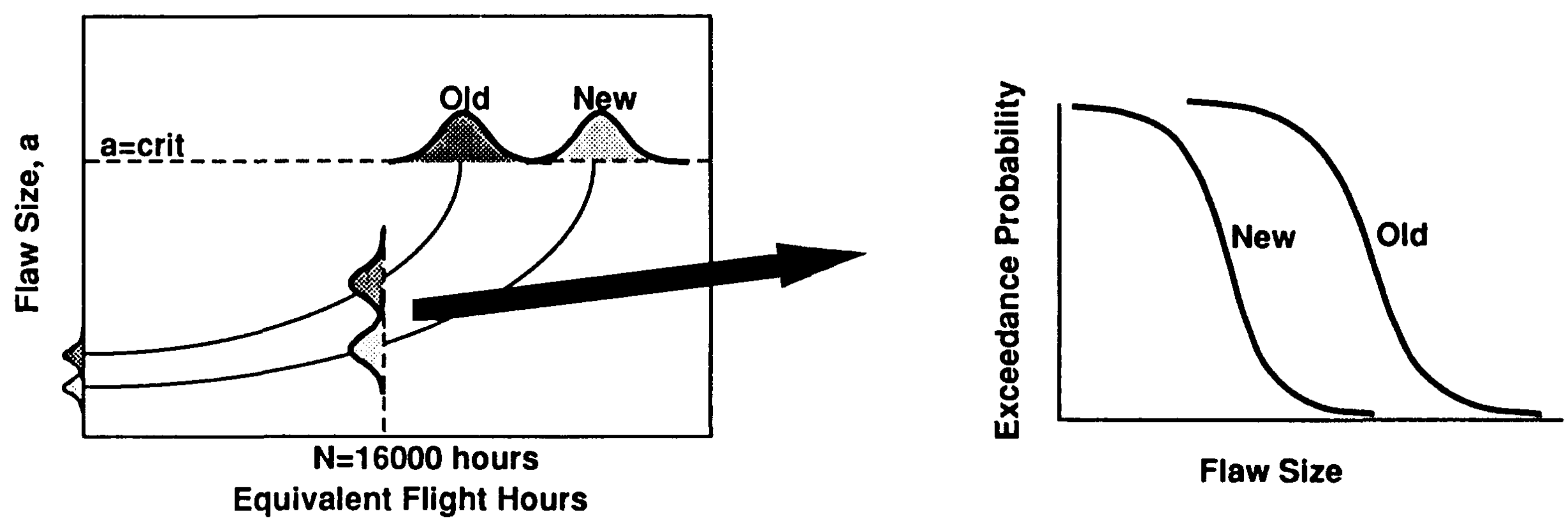
*based on Box-Cox transformation analysis of the data.

Fatigue Durability Quantification

Life Distribution to 0.05 in. Flaw

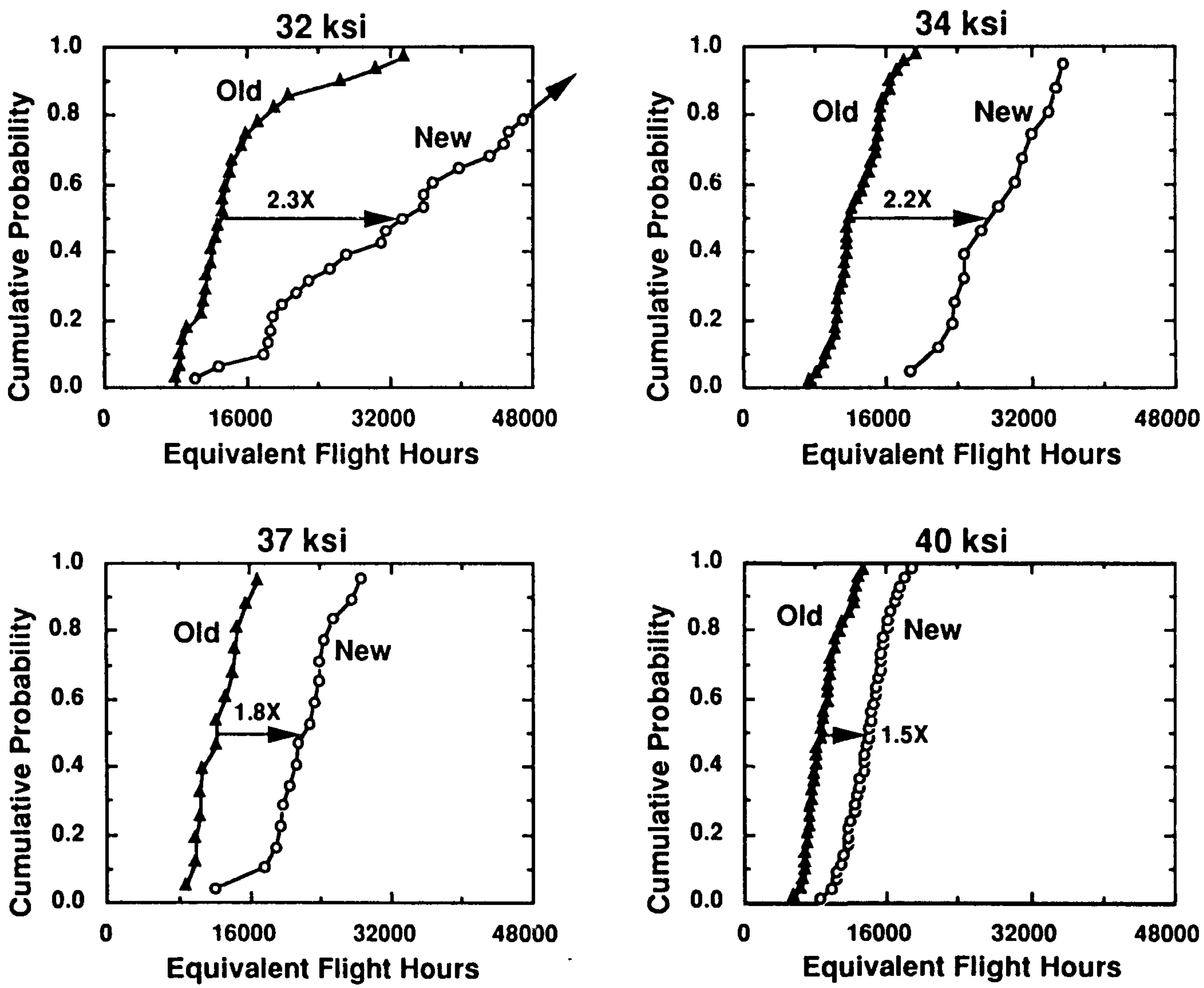


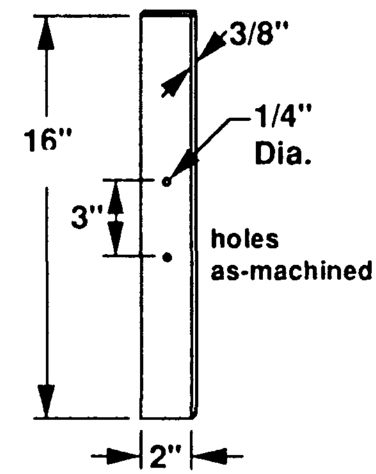
Flaw size Exceedance After Two Lifetimes (16,000 hours)



Effect of Thick Plate Quality on Cumulative Life Probability to 0.05 in. Flaw

Spectrum Peak Stresses of 32, 34, 37 and 40 ksi



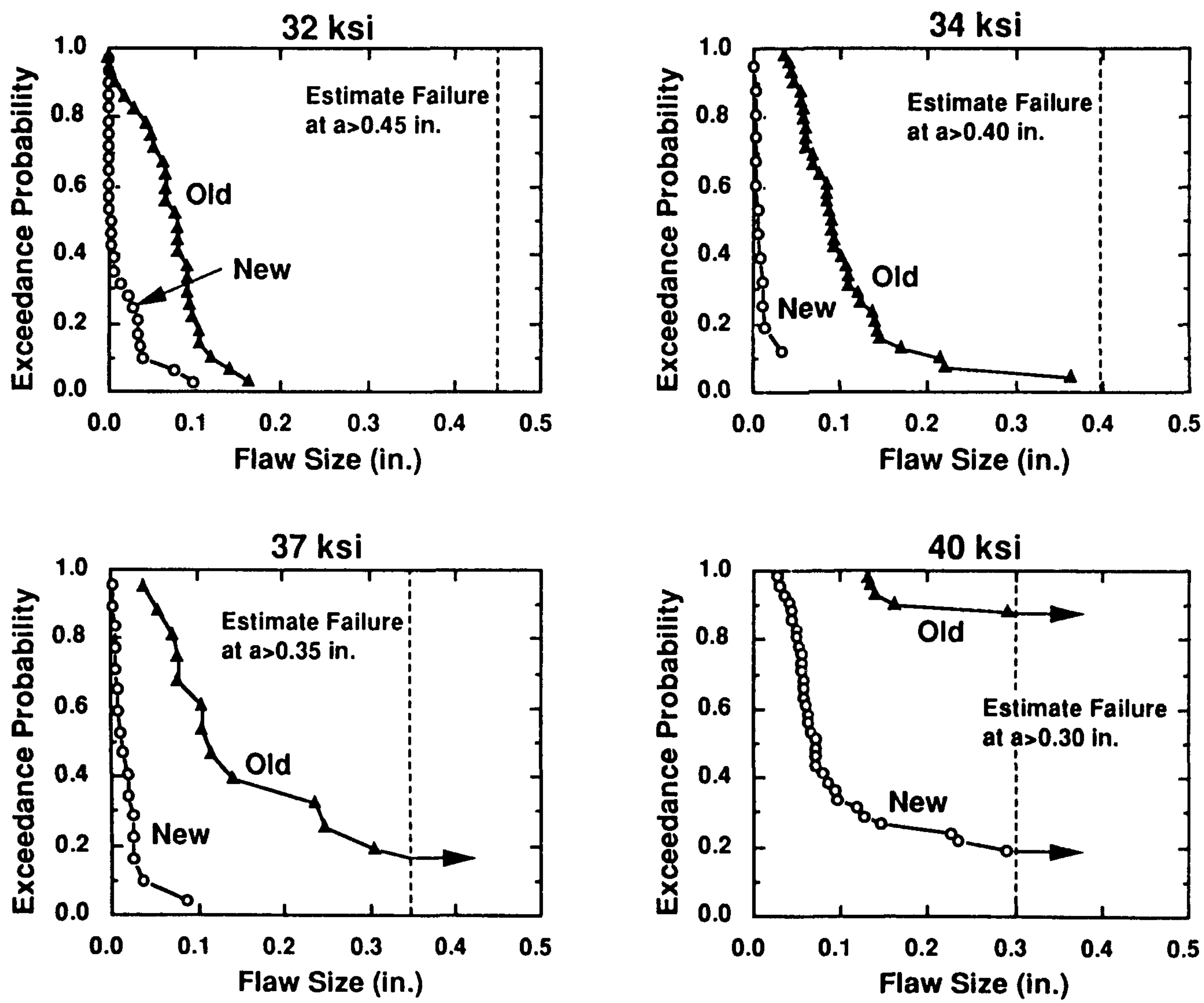


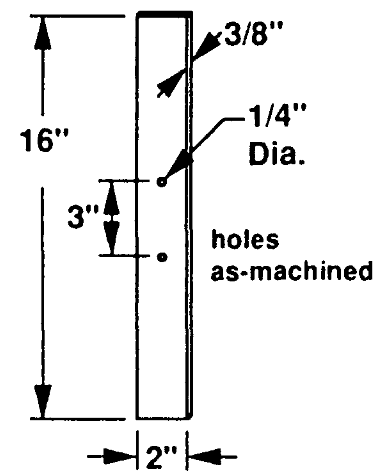
7050-T7451 Thick (5.7 in.) Plate
T/2 Specimen Location
Long Transverse Orientation

F-16 400 Hr. Lower Wing Spectrum
8000 Hours = 1 Service Lifetime

Effect of Thick Plate Qualtiy on Flaw Size Exceedance Probabilities

16000 Hours (2 Lifetimes) at Spectrum Peak Stresses of 32, 34, 37, and 40 ksi





7050-T7451 Thick (5.7 in.) Plate
T/2 Specimen Location
Long Transverse Orientation

F-16 400 Hr. Lower Wing Spectrum
8000 Hours = 1 Service Lifetime

7050 Plate

Hierarchy of fatigue initiating features

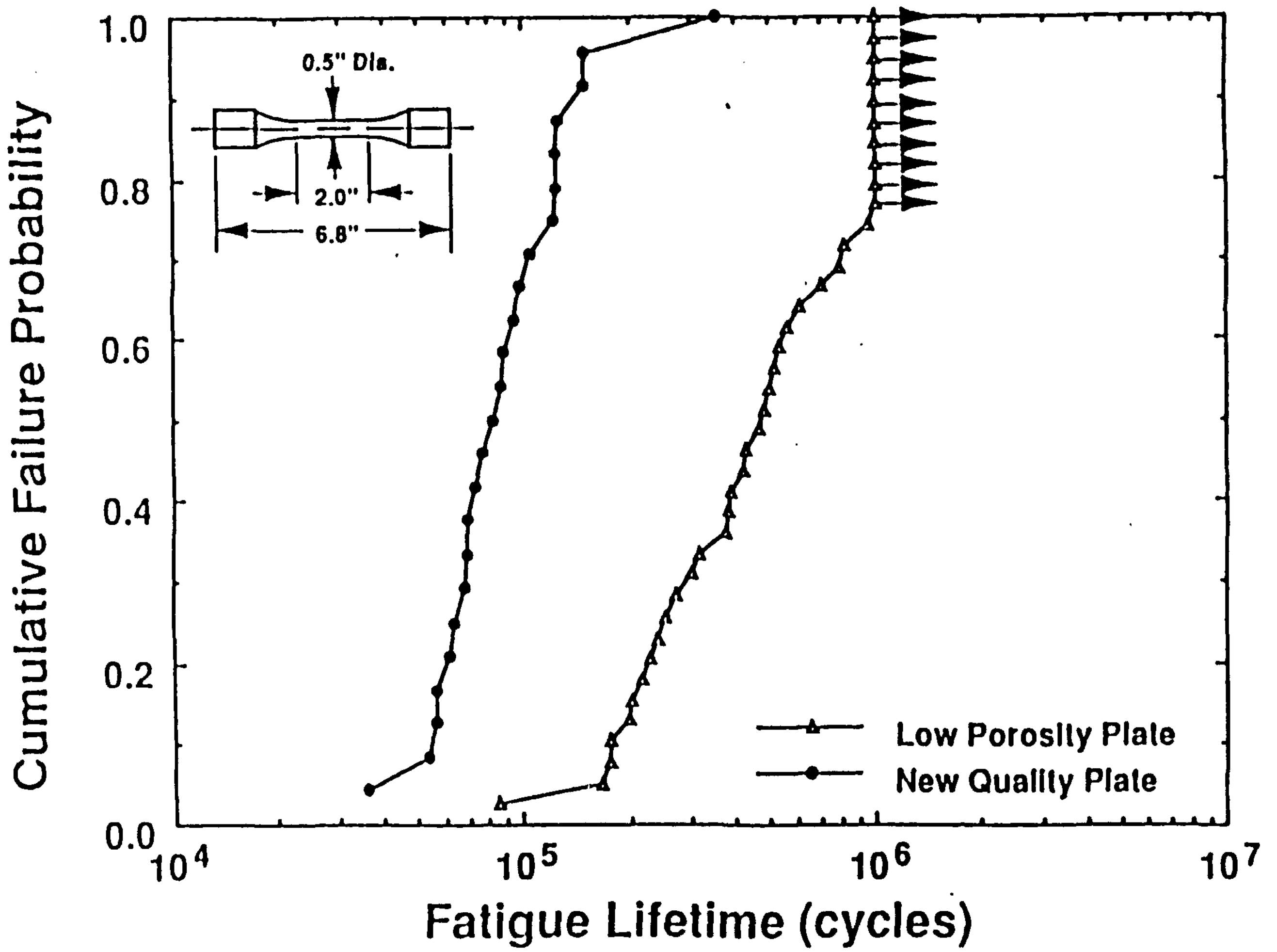
Constant amplitude, R=0.1

Material	Product	Dominant Microstructural Feature		
		Smooth Fatigue	Open Hole Fatigue*	
	Thickness (in.)	(round bars)	As-machined holes	De-burred holes
Old Quality Plate	5.7	Coarse Microporosity	Coarse Microporosity	Coarse Microporosity
New Quality Plate	5.7	Microporosity	Hole Quality/ Microporosity	Microporosity
Low Porosity Plate	6.0	Fine Microporosity	Hole Quality	Constituent Particles
Thin Plate	1.0	Constituent Particles Grain Structure	--	Constituent Particles Grain Structure

*Observations consistent with USAF spectrum fatigue test results (Magnusen et. al., ASIP '92 Conf.)

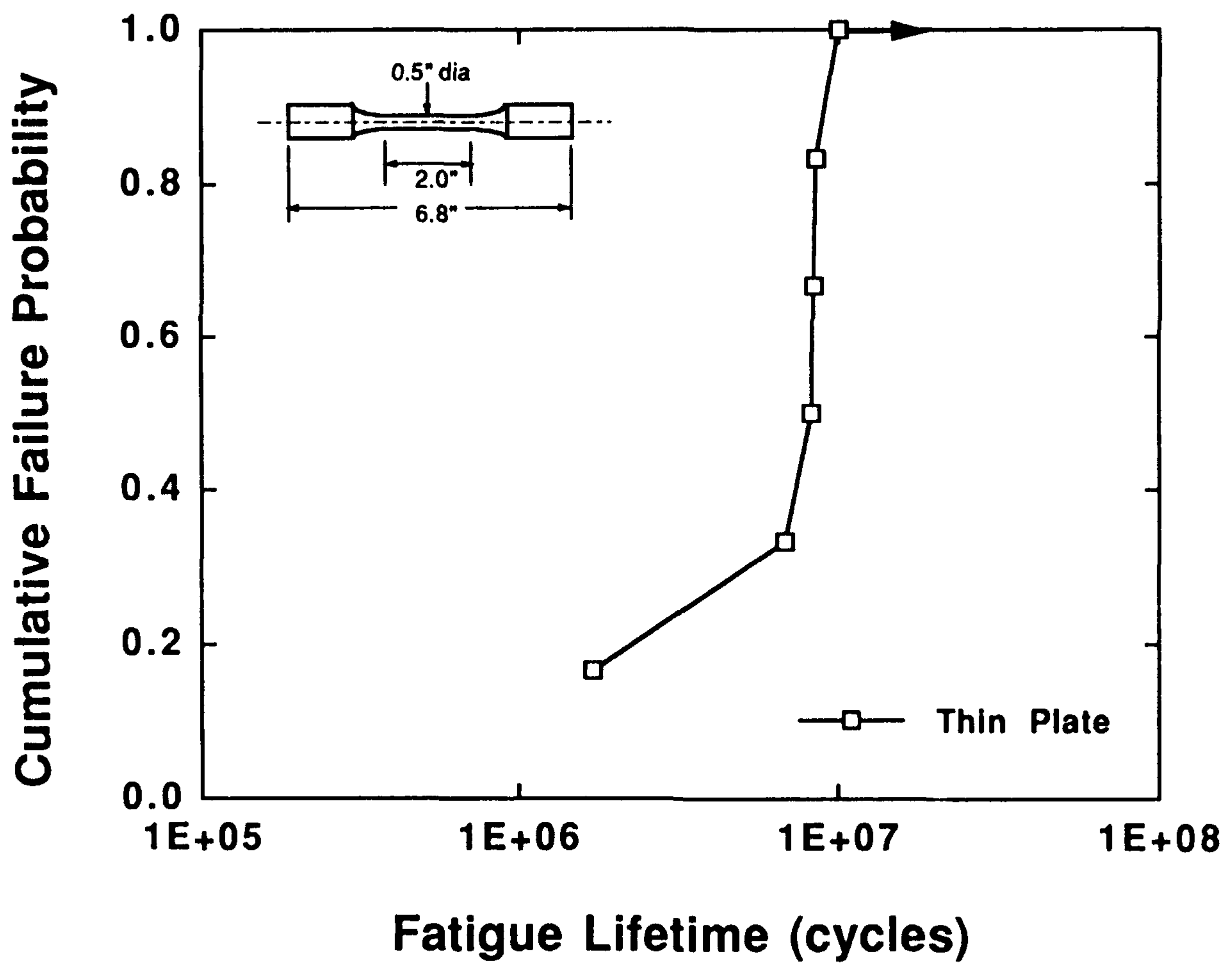
Smooth Fatigue: New Quality and Low Porosity Plate

Cumulative smooth fatigue failure distributions for 7050 new quality plate and low porosity plate tested at a maximum stress of 40 ksi, R=0.1, frequency = 10 Hz, lab air, LT orientation



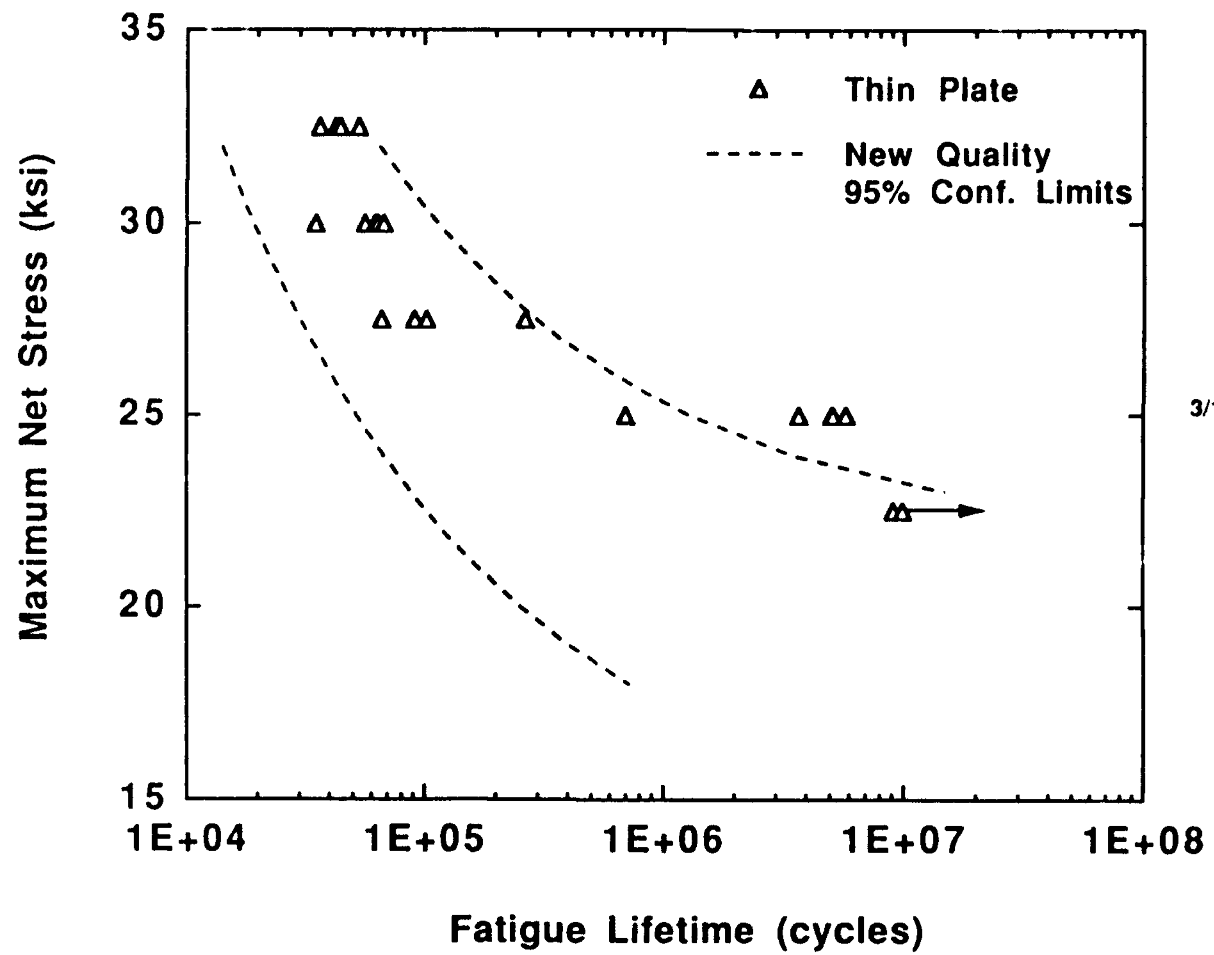
Smooth Fatigue: Thin Plate

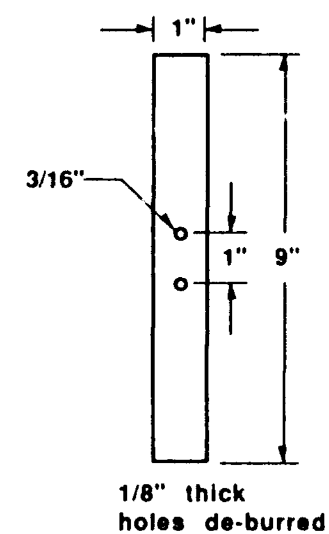
Cumulative smooth fatigue failure distributions for 7050 thin plate tested at a maximum stress of 45 ksi, R=0.1, frequency = 30 Hz, lab air, LT orientation



Open Hole Fatigue: Thin Plate

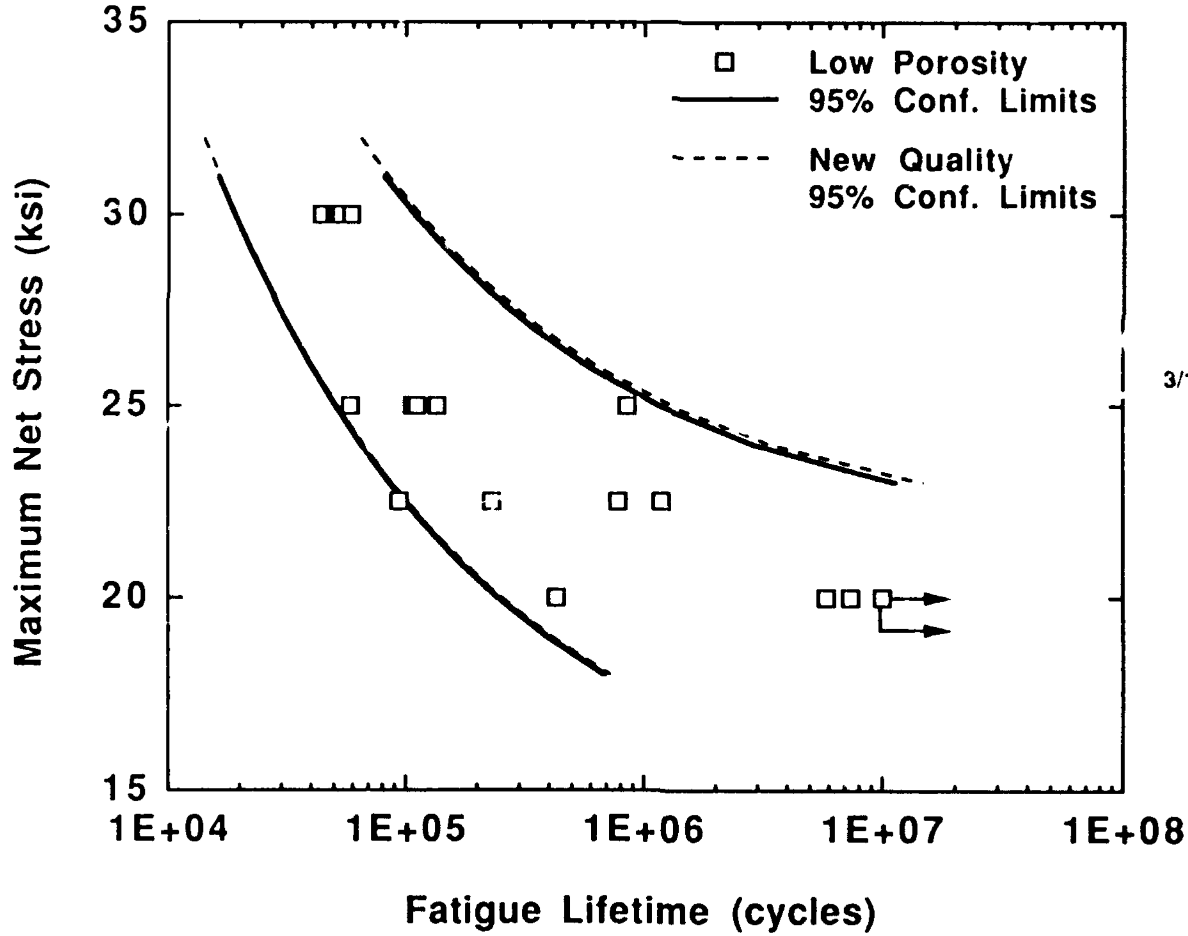
Stress vs. life (S/N) open hole fatigue data for 7050 thin plate and 95% confidence limits for new quality plate, tested at R=0.1, 30 Hz, LT orientation, lab air

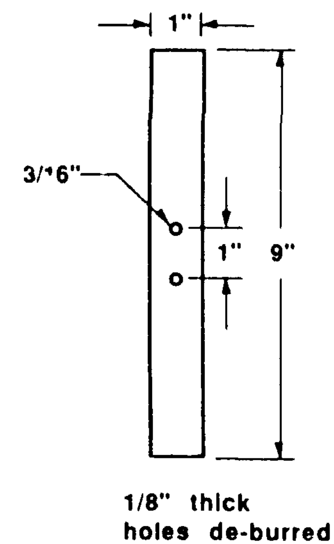




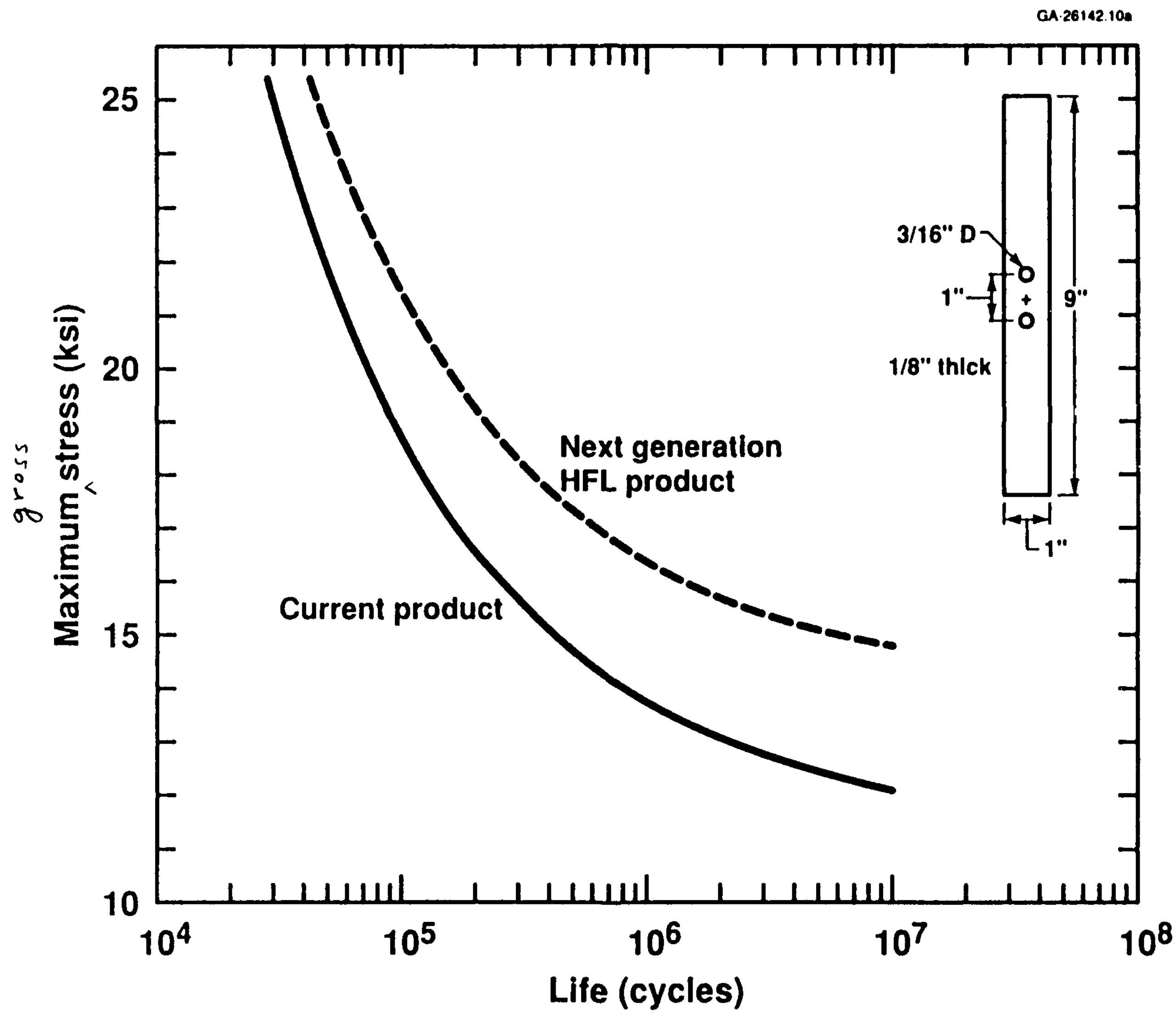
Open Hole Fatigue: Low Porosity Thick Plate

Stress vs. life (S/N) open hole fatigue data for 7050 low porosity plate and 95% confidence limits for new quality plate, tested at R=0.1, 30 Hz, LT orientation, lab air





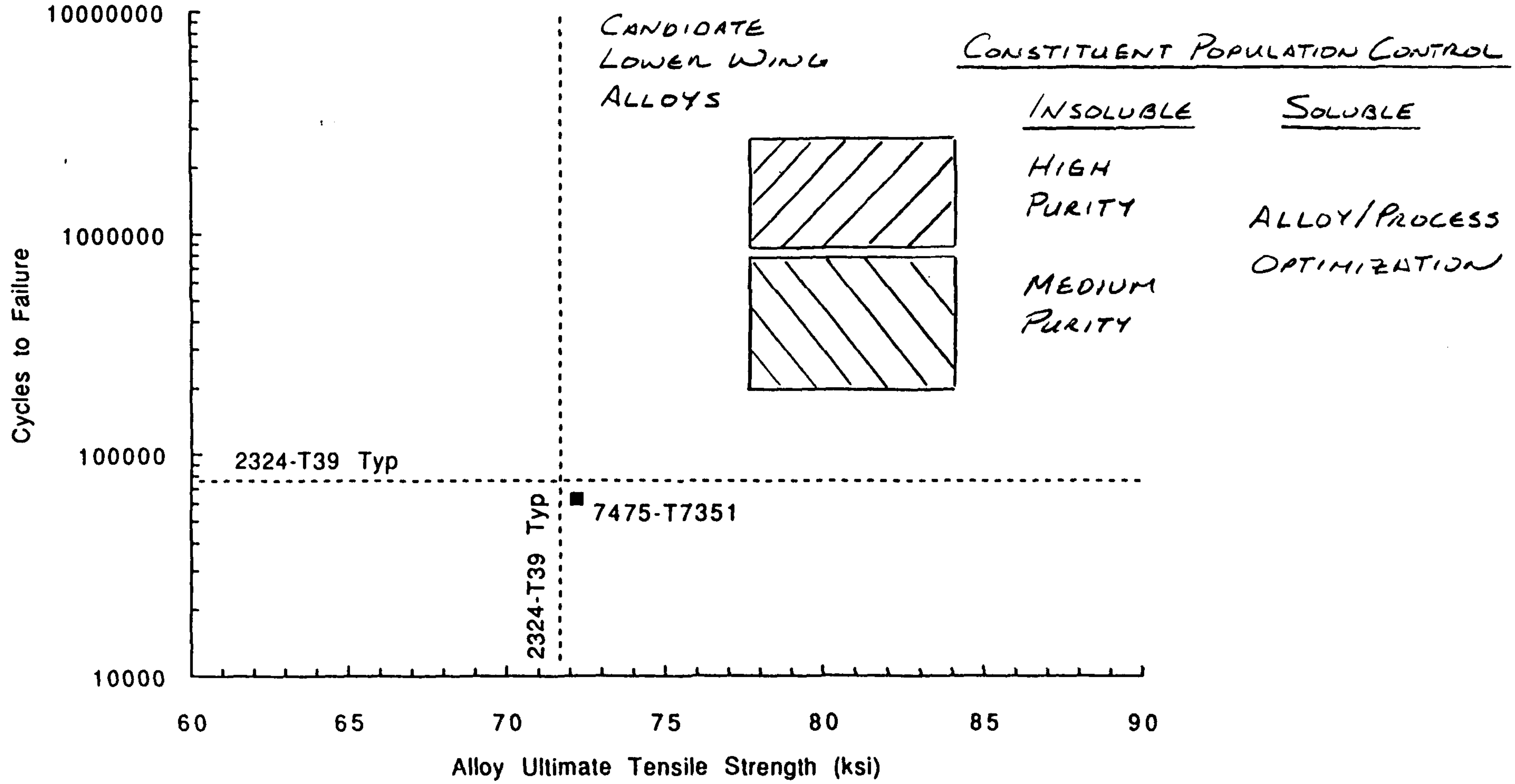
Projected Open Hole Fatigue Improvement
7050-T7451 Thick Plate (4-6 in.)
(Long Transverse, T/2 Test Location, R = 0.1)



Fatigue Life* of Lower Wing Plate (nom. 0.75" thick) Candidates at Net Section

Stress= 29 ksi

*Two-hole, Kt=2.5, t=0.125", W=1", D=0.187"



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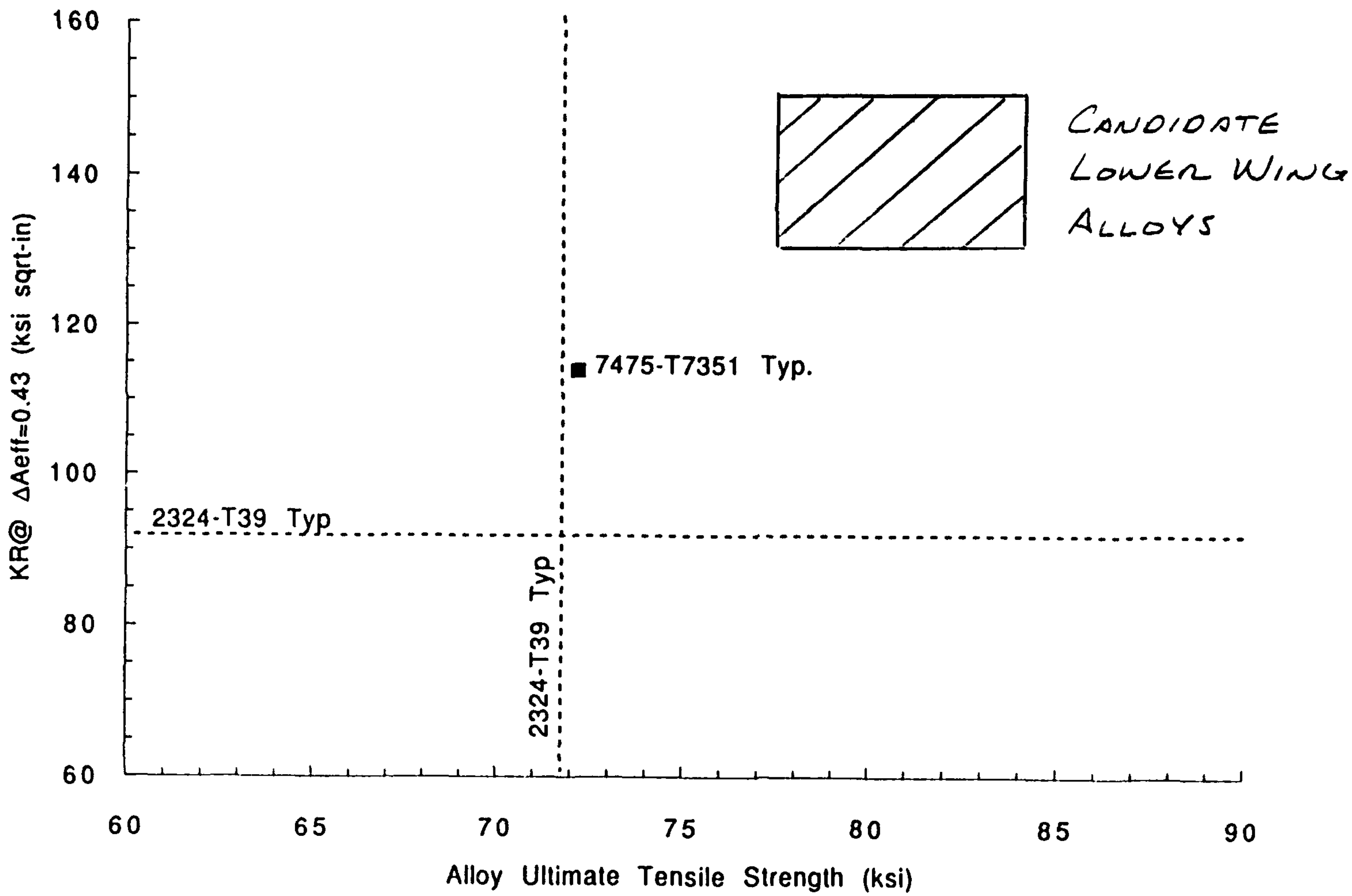
Fracture Toughness* of Lower Wing Plate (nom. 0.75" thick) Candidates

* C(T) Specimen, W=8", B=0.5"



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Effect of Particle Content on Open Hole Specimen Fatigue Strength of 7XXX Aluminum Alloy Plate (0.375 in. thick)

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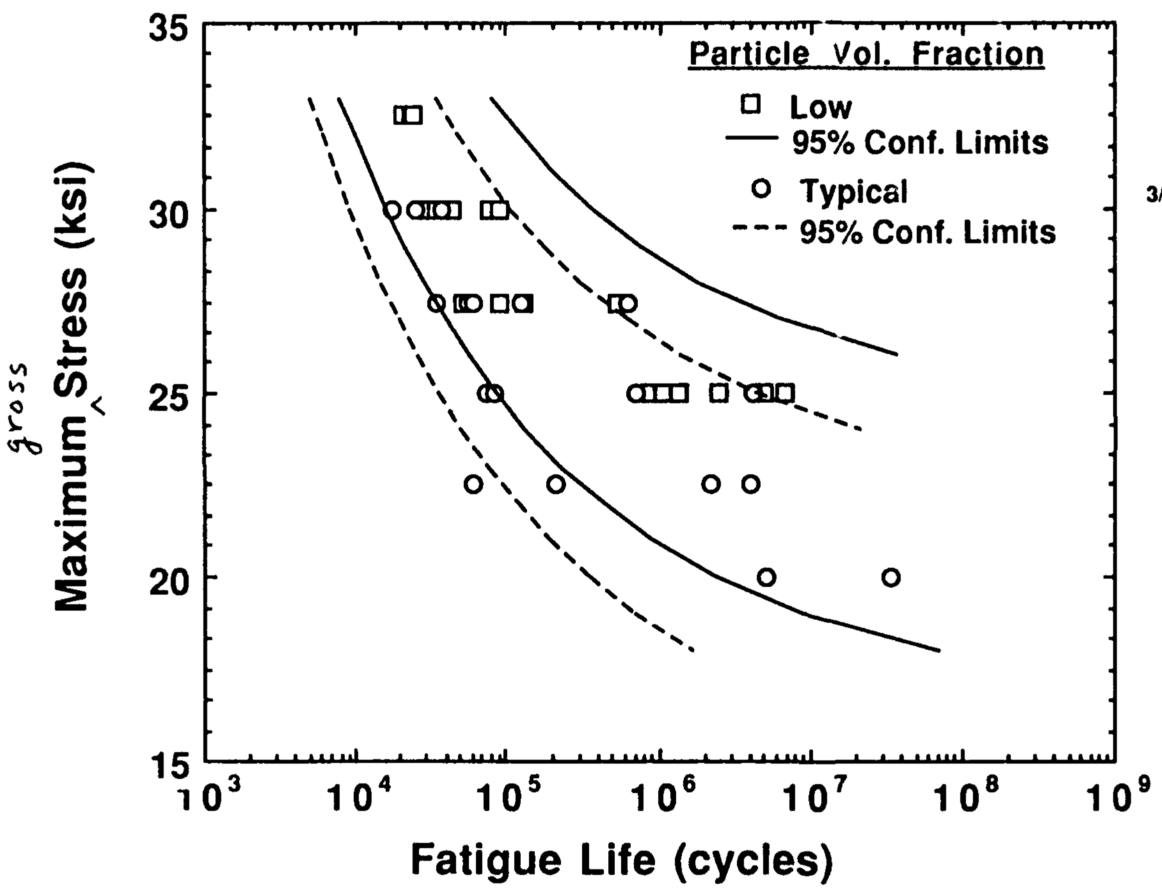
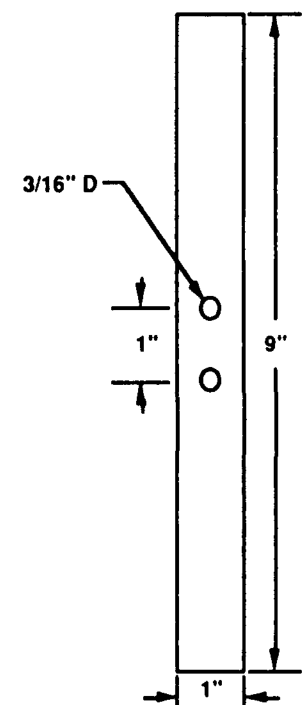
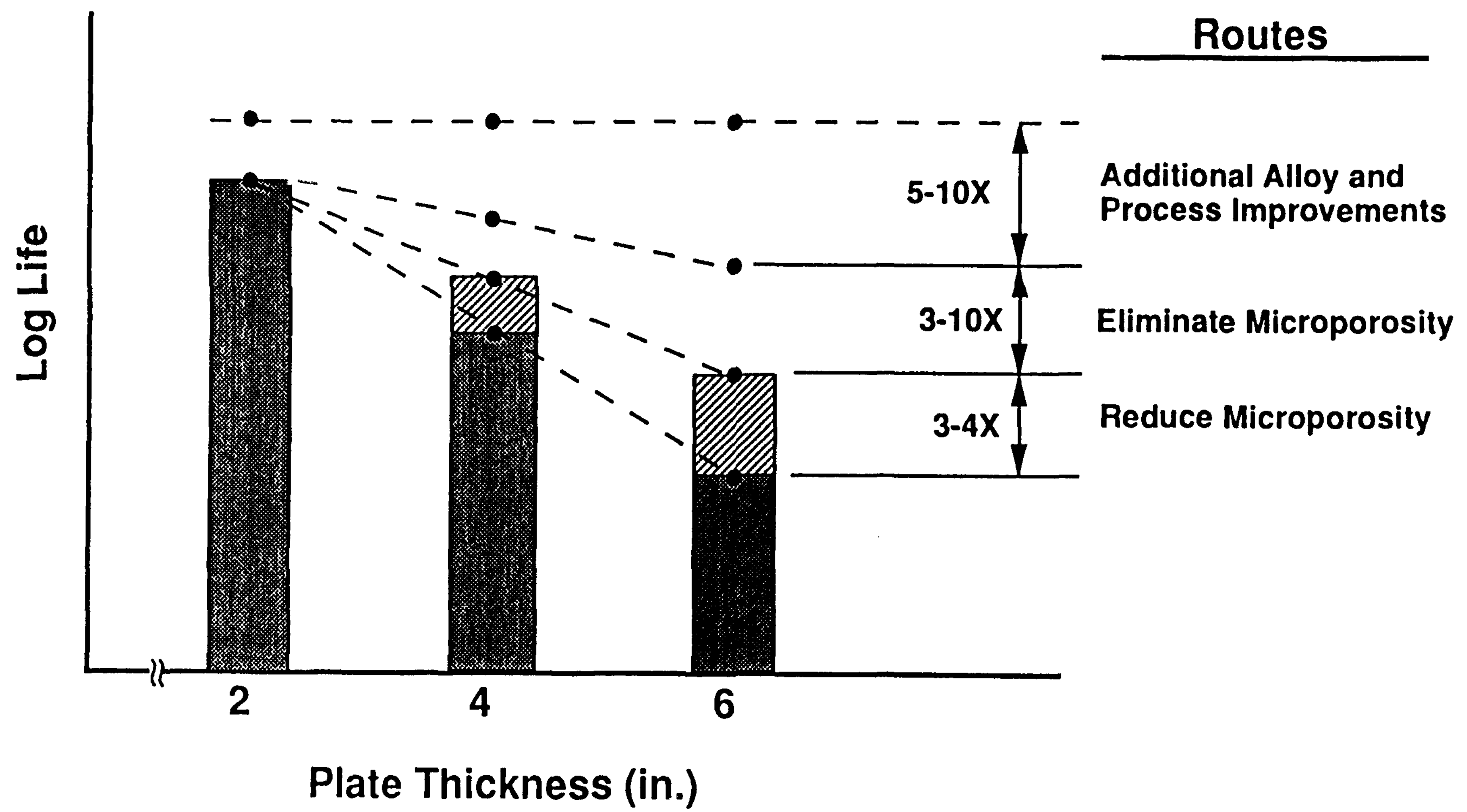
Material Reliability





Frequency = 25Hz
Stress Ratio = 0.1
Long Transverse

Potential Fatigue Durability Improvement Through Material Quality



Intrinsic Microstructural Inhomogeneities That Could Affect Fatigue Durability

Material	Feature
Castings	Porosity
High strength alloys	Coarse constituents
Thick products	Porosity/constituent particles
Powder metals	Inclusions
Al-Li	Coarse constituents
Superplastic parts	Cavities
MMC's	Particulate/fibers
Weldments	Porosity/inclusions
Structural ceramics	Microcracks

Barriers to Exploitation

Fatigue Quality Improvement

- Initial cost premiums attached to long term durability a hard sell
- Fatigue design practices
- Understanding role of microstructure
  - Designer misconceptions
  - Pathology of structural failures

Barriers to Exploitation
Fatigue Quality Improvement

- Initial cost premiums attached to long term durability a hard sell
  - Current design and procurement specifications fail to discriminate effect of metal quality
  - Accurate projection to life cycle cost saving difficult
  - Weight and manufacturing cost saving opportunities often overlooked
  - Development cycle cost saving hidden
  - T/E investment required to verify product differentiation

Barriers to Exploitation (continued)
Fatigue Quality Improvement

- Fatigue design practices
  - Largely empirical; airframers vary in their approach
  - Provider data bases generally held proprietary and not widely shared within the industry
  - Empirical approach uncovers problems too late when change is difficult
  - Design for worst case flaw does not address potential for widespread cracking in the fleet
  - Full scale durability validation article is not a statistical test
  - USAF developed durability design methodology little used because it is cumbersome and providers disagree on incentives for use
  - Fatigue quality data base does not exist

Barriers to Exploitation (continued)
Fatigue Quality Improvement

Understanding role of microstructure:

- Designer misconceptions
  - Metal quality effect overridden by scatter in fatigue testing
  - Notched component and structural joint fatigue testing offsets metal quality effect
  - Metallic inhomogeneities are secondary to mechanical nicks and dings as sources for problem fatigue cracks
- Pathology of structural failures
  - Complexity or lack of microstructural interpretation
  - Unavailable statistical data to sway designers

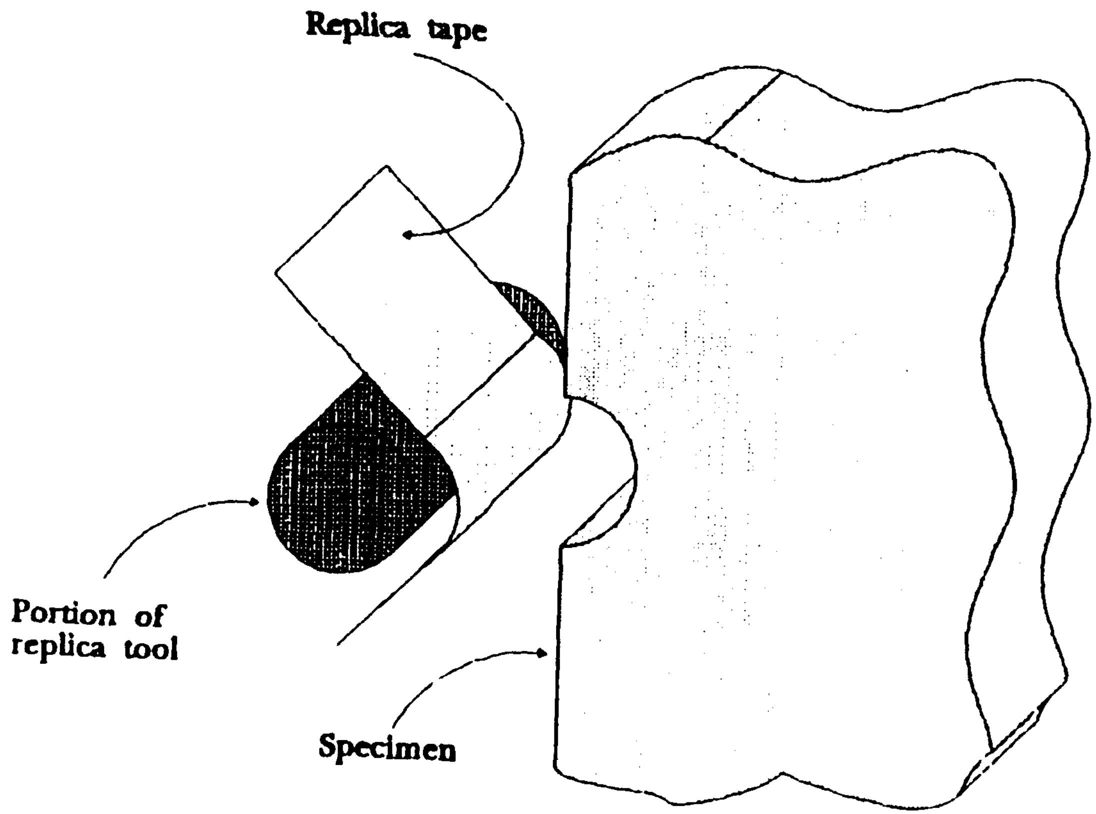
Program Expectations
Deliverables

- Data and supporting documentation with clear vision on how to capture benefit of improved quality materials and processes
  - Background information and alloy 7050 experience
  - Validation of fatigue quality improvement concept
  - Quantification of payoff potential
  - Hard evidence to facilitate procedural changes
  - Test/evaluation protocols to reduce R&D time and cost
  - Technology transfer examples
- Microstructure and fatigue characterization of 7050 product variants
  - Quantitative description of microstructural features important to fatigue and their relationship to both random microstructure and performance
- Microstructure based life prediction model(s)
  - Validation of crack growth based approach to describe material quality influence on fatigue damage accumulation
  - Link with general purpose probabilistic analysis software
- Description of test/evaluation methodologies developed to accomplish the above
- Readiness for scale-up technology demonstration program
  - Life assessment methodology
  - New products
  - Thick parts

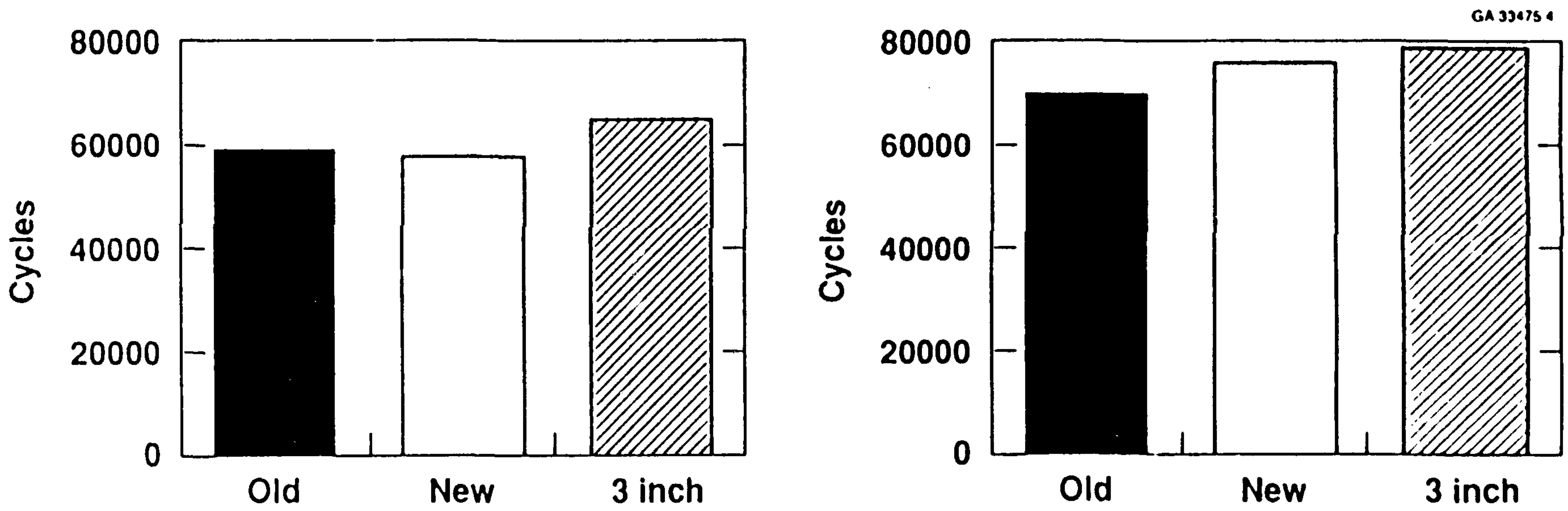
Experimental Procedures

Replication Method for Measuring Small Cracks

- Acetate tape produces an exact replica of notch surface when acetone is applied



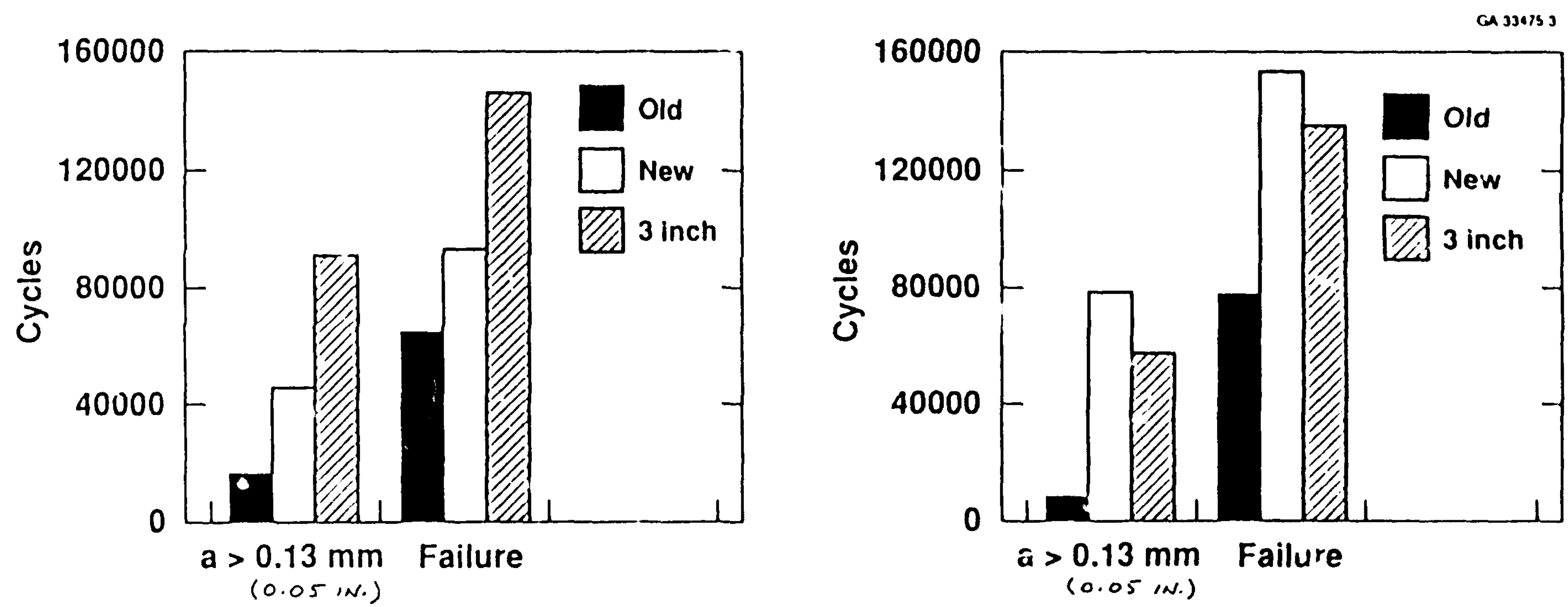
Average Crack Growth Life Remaining following Development of an Initial Crack Size 2a>0.13 mm
(0.05 IN.)



a) Gross stress 124 MPa
(18 KSI)

b) Gross stress 110 MPa
(16 KSI)

Summary of Notch Specimen Fatigue Tests for Various Materials



a) Gross str ;ss 124 MPa
(18 KSI)

b) Gross stress 110 MPa
(16 KSI)

Modeling Chronology

Coupon to structure:

- Quantify potential for structural payoff
  - Performance benefit attributed to higher quality initial product
  - Risk of widespread fatigue damage
  - Reliability based inspection intervals

Coupon S-N to fatigue initiating feature & vice-versa:

- Validate LEFM methodology
  - Equivalent flaw concept
  - Crack growth base model
  - Stress intensity factor solutions
  - Back calculation of pore/particle sizes from test lives
  - Effect of specimen geometry and microstructure
- Probabilistic crack growth analysis
  - Link to general purpose probabilistic analysis software (PROBAN)
  - Input size and location distributions for crack starting features
  - Prediction of scatter in S-N fatigue behavior
  - Back calculation fatigue initiating particle distribution
- S-N prediction among 7050 variants

Random plane microstructure to coupon S-N behavior:

- Scaling random plane microstructure to extreme value distribution of fatigue initiating features
- Plasticity adjusted damage accumulation model (no empirical fitting required)

The EIFS Distribution
Starting Point for Life Management at Various Structural Levels

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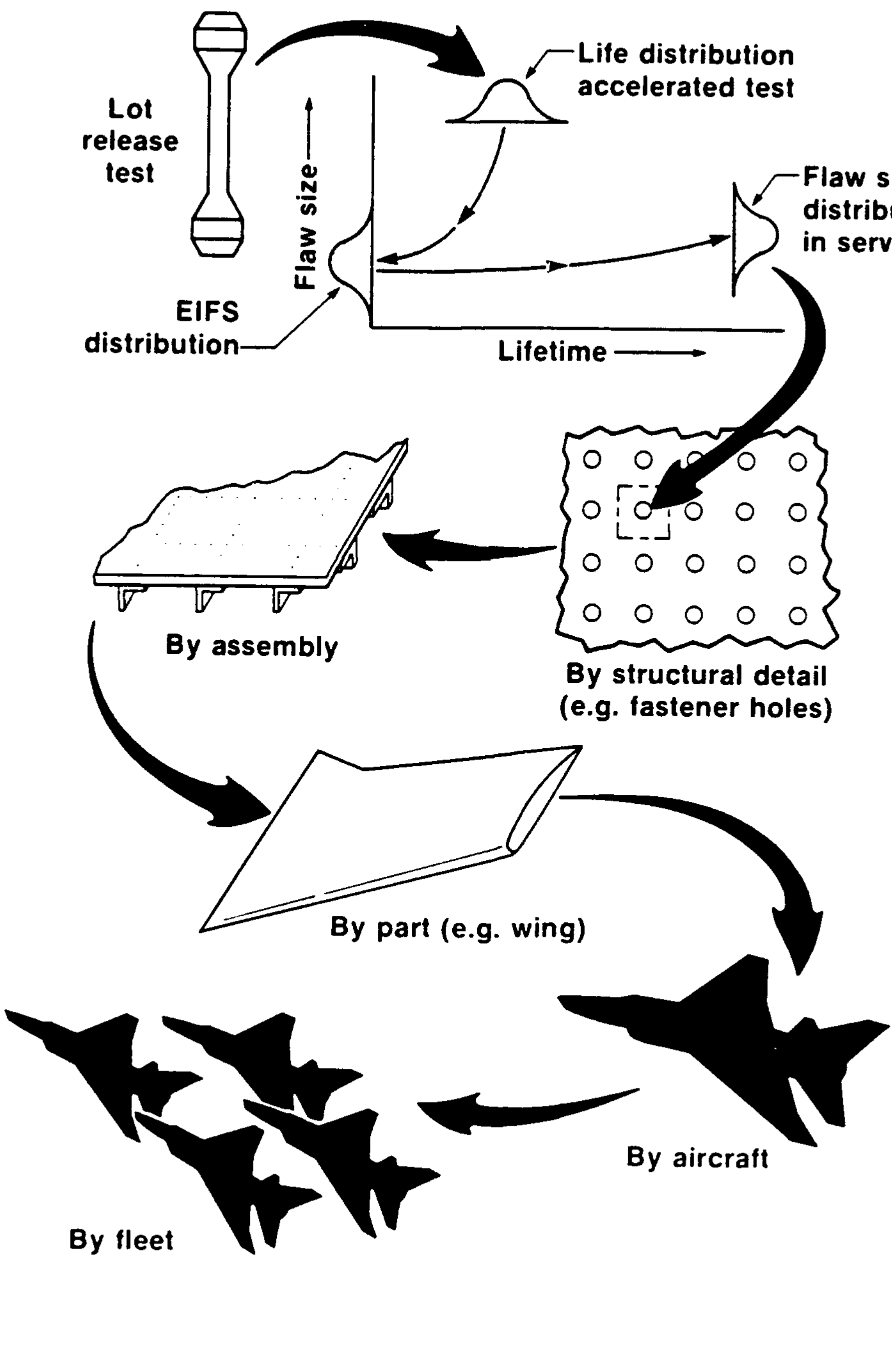
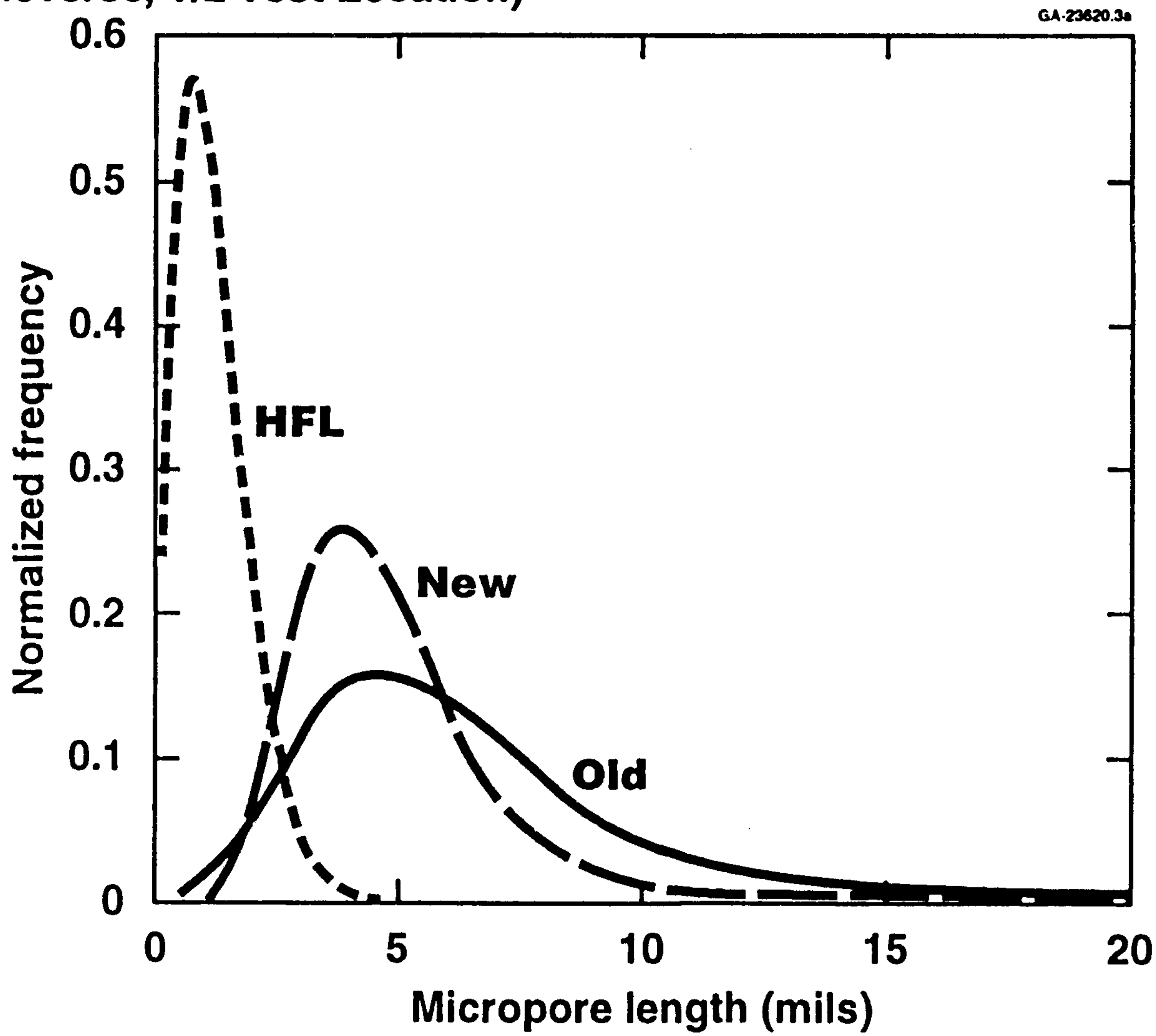
Material Reliability



Crack-Initiating Micropore Size Distributions

7050-T7451 Thick Plate Smooth Fatigue Failures (Long Transverse, T/2 Test Location)



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Hypothetical Durability Analysis

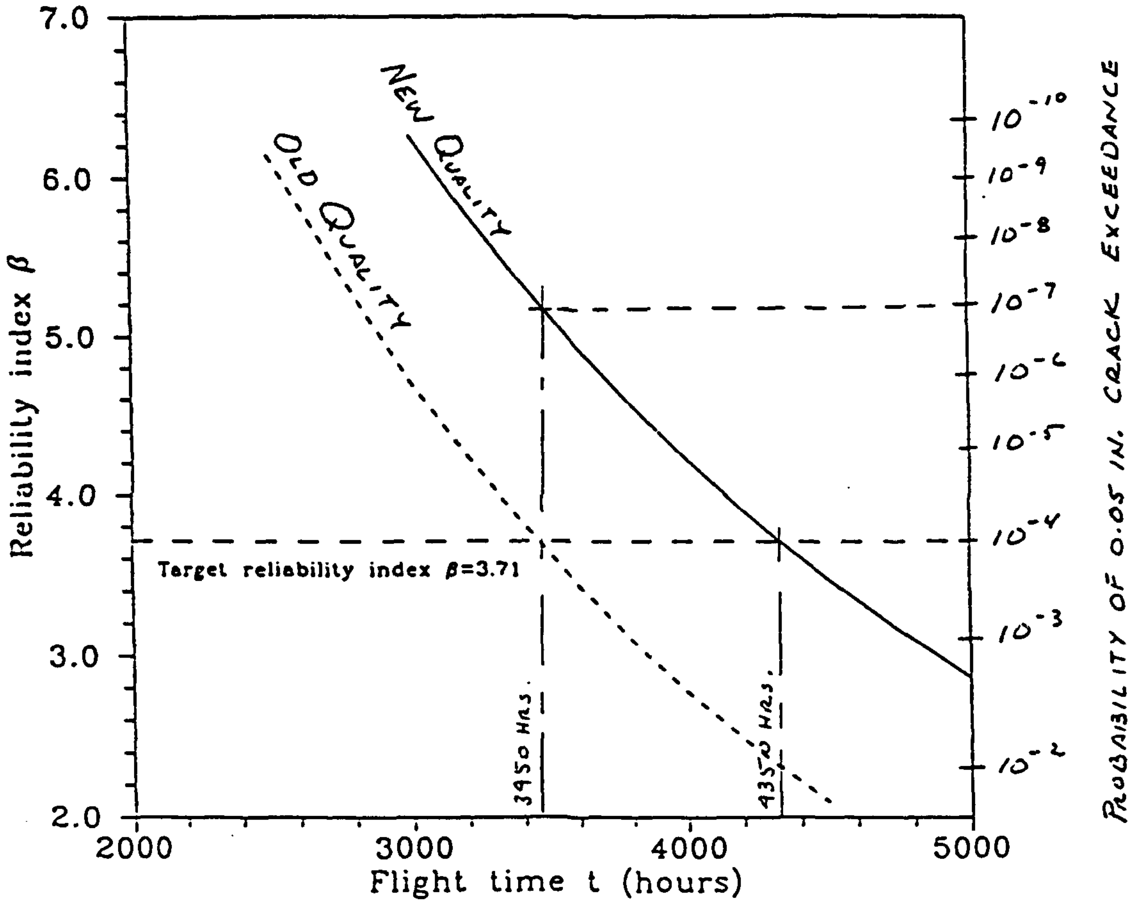
7050-T7451 Thick Plate

Calculated crack growth potential out of F-16 lower wing skin fastener holes (M.E. Artley, USAF, 88-04-15)

	Number of flaw size exceedances per 1000 holes					
	1 service lifetime (8000 flt. hrs.)			2 service lifetimes (16000 flt. hrs.)		
Flaw size (in.)	Old quality material	New quality material	HFL material	Old quality material	New quality material	HFL material
0.03	196	3	0	850*	850*	44
0.05	2	0	0	633	499	1
0.10	0	0	0	195	3	0
0.20	0	0	0	3	0	0

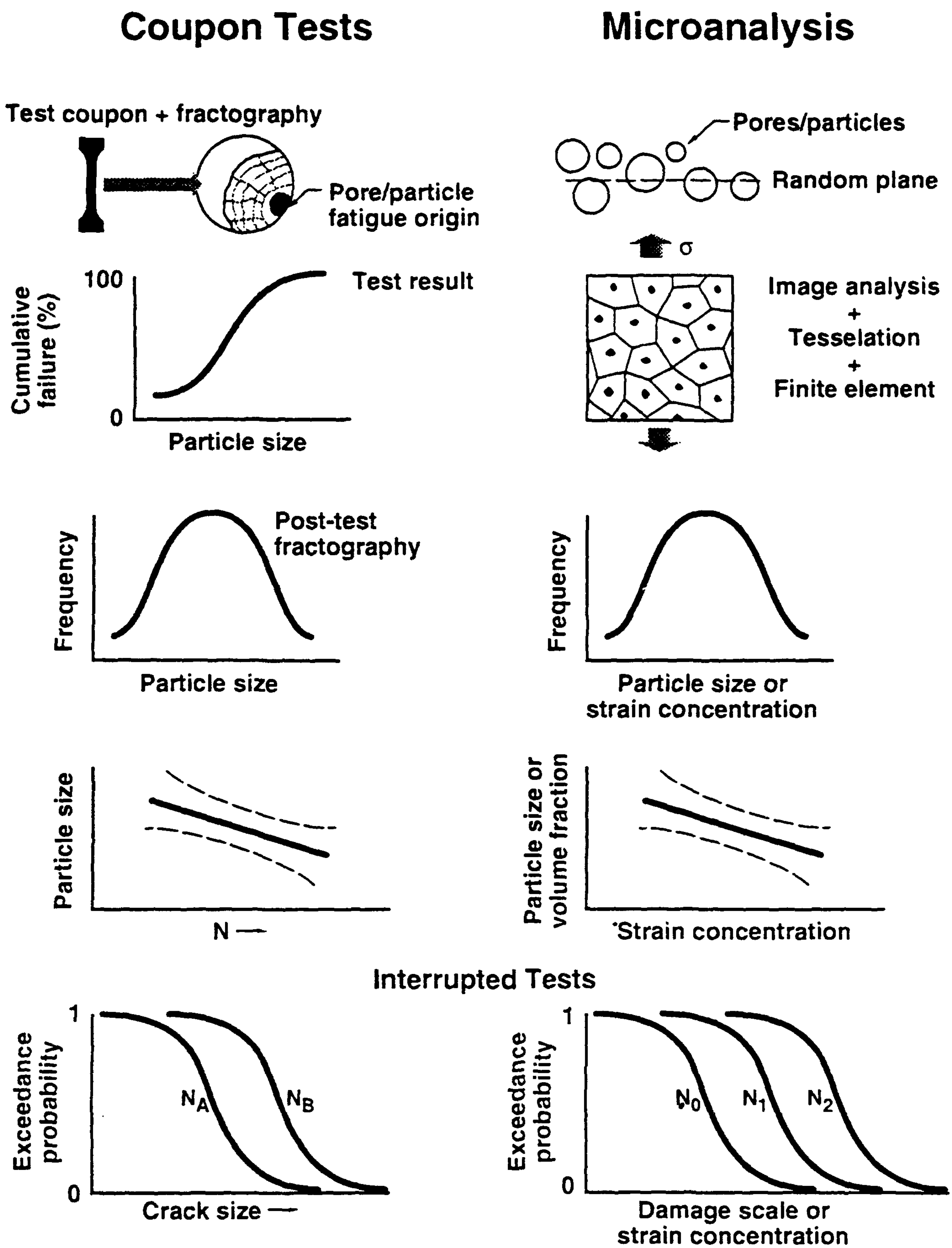
Calculated Fastener Hole Reliability of Old and New Quality 7050 Thick Plate

- Reliability measured by flight hours to achieve a 0.05-in. (inspectable) crack extension from an undamaged hole
- Calculations based on probabilistic evaluation of fatigue crack growth and micropore population in the original material
- The analysis considered spectrum fatigue loading to represent a military fighter application



Results:

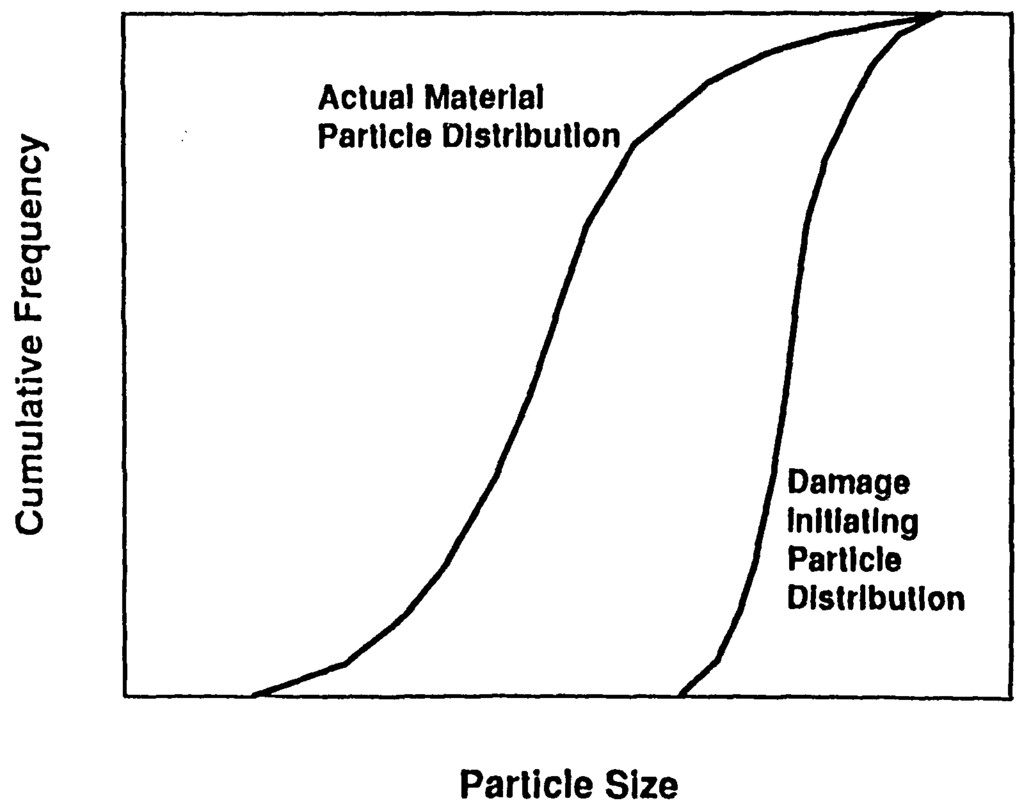
- Structural reliability inreases with new quality material (reduces widespread damage risk)
- Flight hours with 10^{-4} probability of finding a crack greater than 0.05-in.:
  - Old quality: 3450 hours
  - New quality: 4350 hours (26% increase in time to first inspection)
- Probability that a crack longer than 0.05-in. would appear at 3450 flight hour inspection:
  - Old quality: 10^{-4} (one chance in ten thousand)
  - New quality: 10^{-7} (one chance in 10 million)



Coupon Tests
Microanalysis
Test coupon + fractography
Pore/particle fatigue origin
Pores/particles
Random plane
σ
Test result
100
0
Cumulative failure (%)
Particle size
Image analysis + Tesselation + Finite element
Post-test fractography
Frequency
Particle size
Frequency
Particle size or strain concentration
Particle size
N
Particle size or volume fraction
Strain concentration
Interrupted Tests
1
0
Exceedance probability
N_A
N_B
Crack size
1
0
Exceedance probability
N_0
N_1
N_2
Damage scale or strain concentration

Constituent Particle Size Distributions

Schematic illustration of the distribution of particle sizes in a material and the distribution of particle sizes which initiate fatigue damage



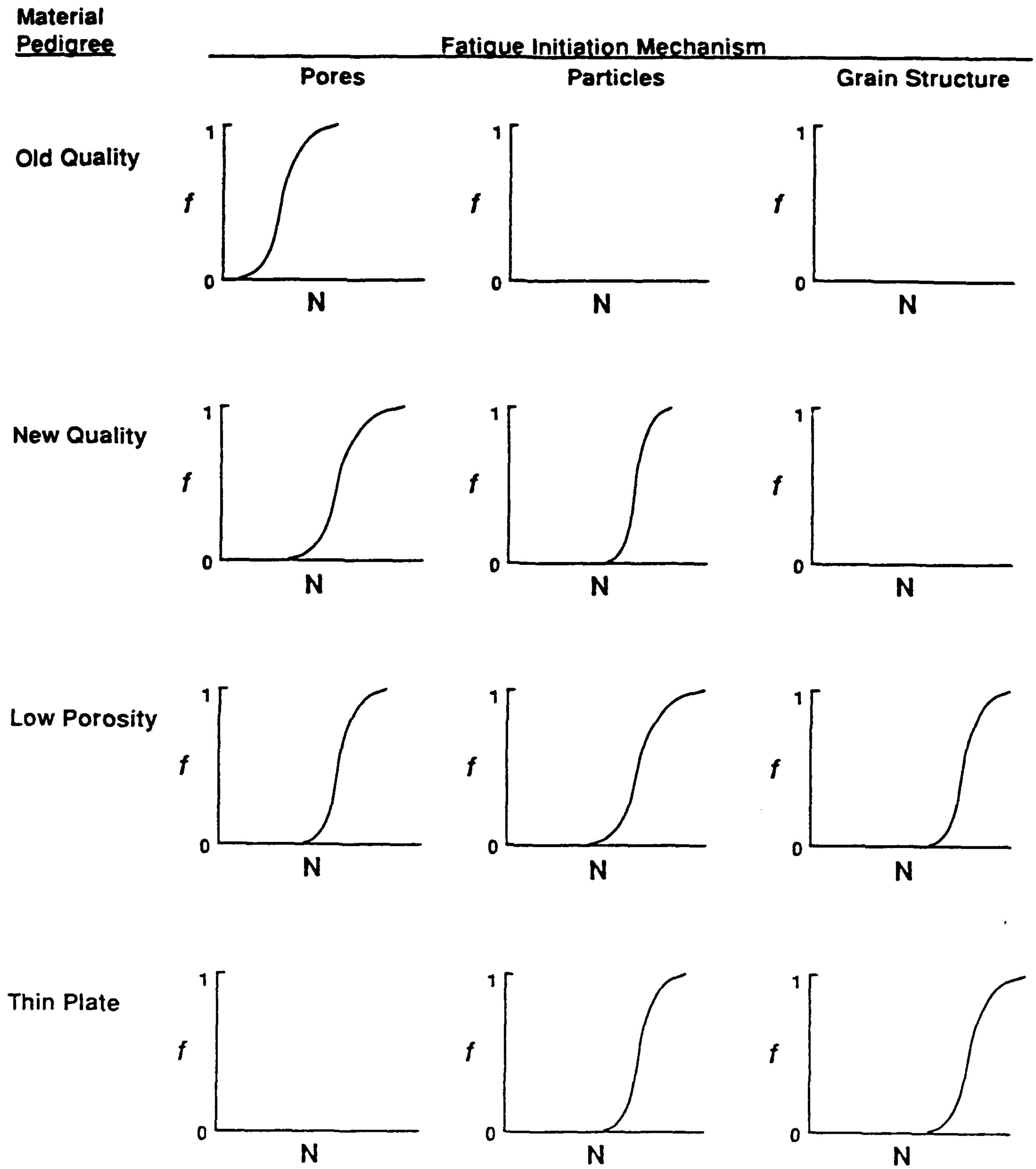


Figure 1. Schematic representation of cumulative probability plots of fatigue lifetime for the four variants of 7050 plate separated on the basis of fatigue initiation mechanism.

STATUS

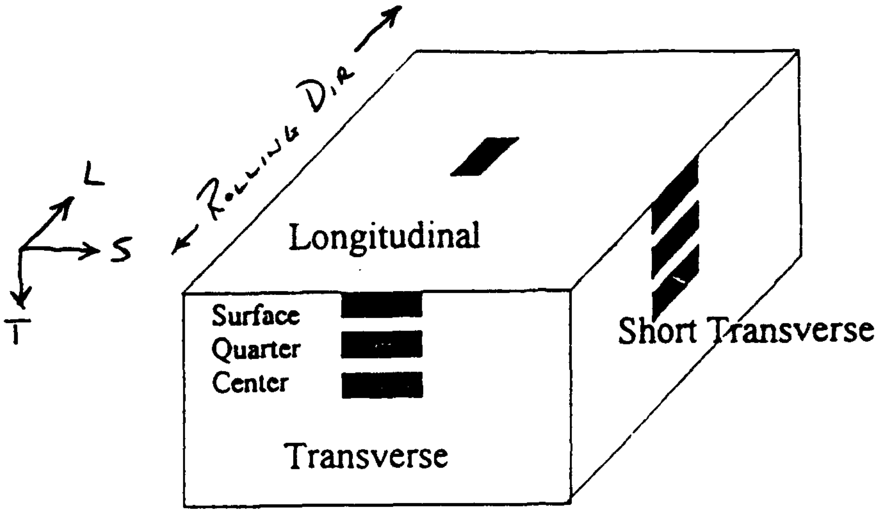
Characterization of 7050-T7451 alloys - *New and old*

Initial microstructures - averages and distributions

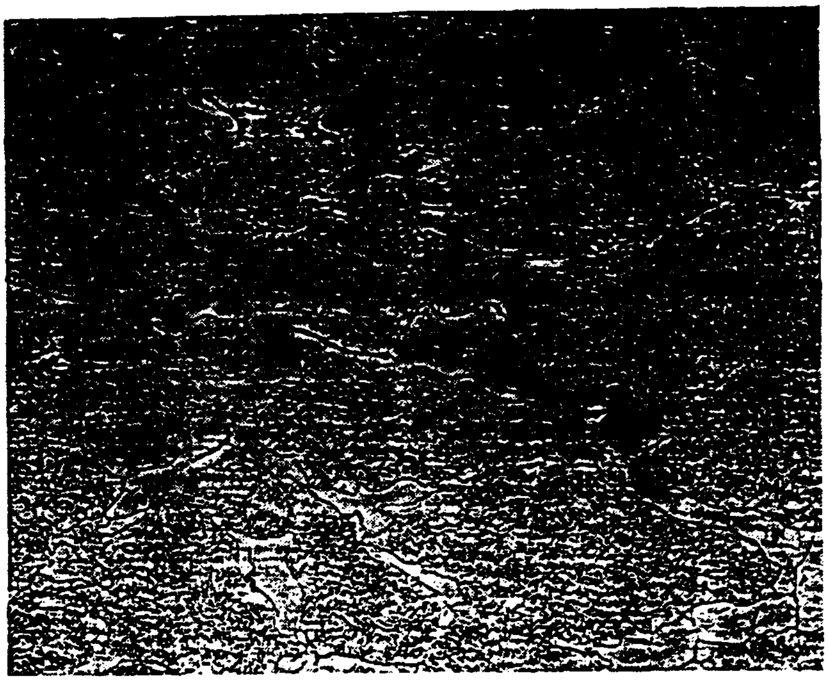
- ✓ Porosities, Constituent Particles, Precipitates
  Sizes, spacings, local volume fractions
- ✓ Grains, Subgrains
  Sizes, shapes, recrystallization levels
- ✓ Improved Statistics

Damage Assessment

- ✓ Fractography
  Facets orientation distributions, fractal dimensions, roughness parameters
- ✓ Crack Path
  Features, geometry, microcracks, dislocation structure, transgranular vs intergranular

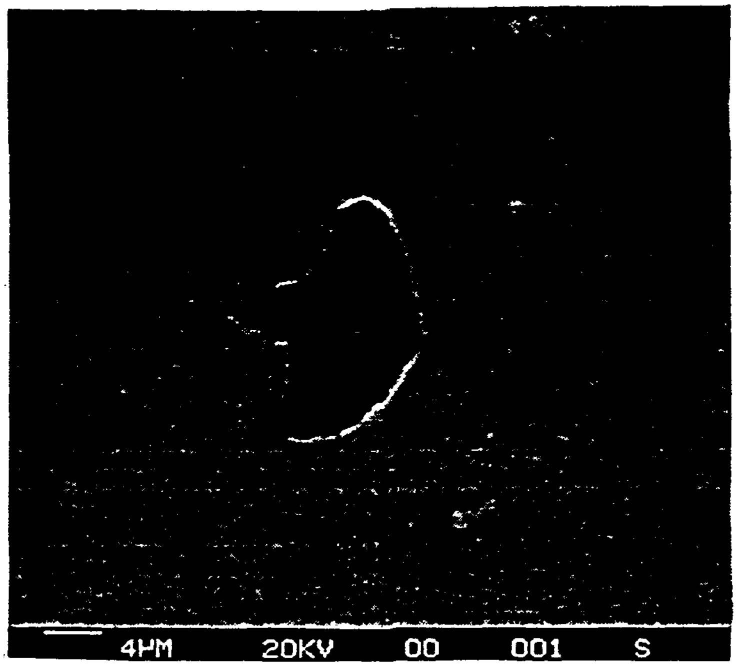


Schemetic of the locations of the specimens in the plate of Al 7050 alloy.

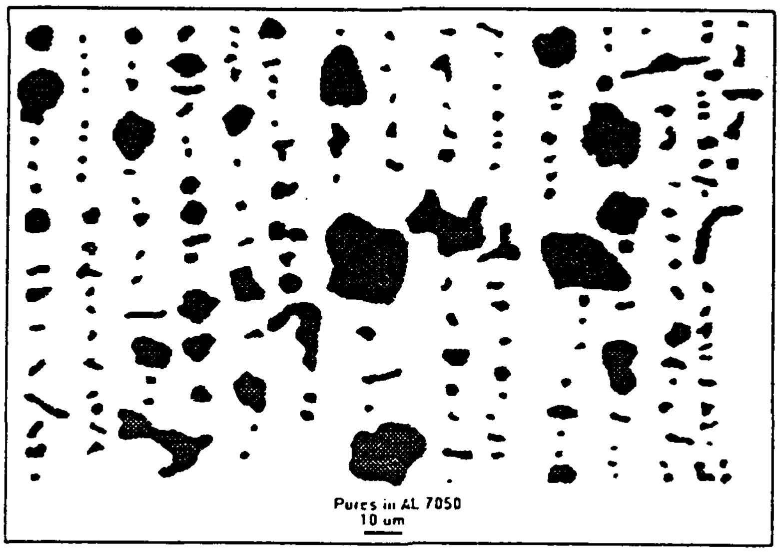


180 μm

The grain structure of the 7050 Al plate alloy. The light grains are recrystallized and the dark ones are unrecrystallized grains with subgrains. The dark spots are the sites where the constituent particles.



A typical pore in the 7050 Al plate alloy.



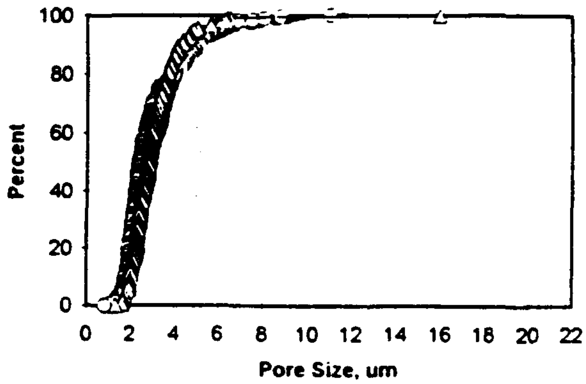
A collection of 201 pores in the transverse * center section of the old pedigree Al 7050 plate alloy. These pores are collected from 180 micrographs.

defined by vector (LS PLANE)

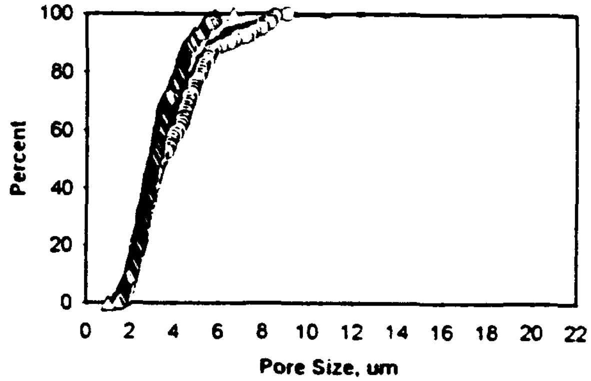
PORES.XLS

S VECTOR
LT PLANE

Old pedigree, longitudinal

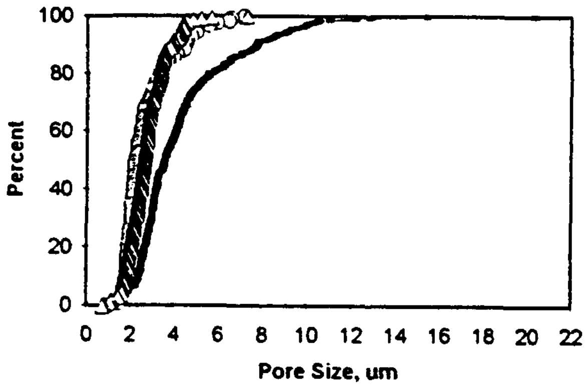


New pedigree, longitudinal

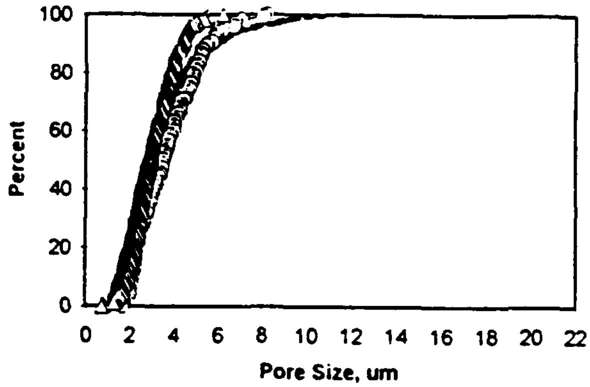


T VECTOR
LS PLANE

Old pedigree, short transverse

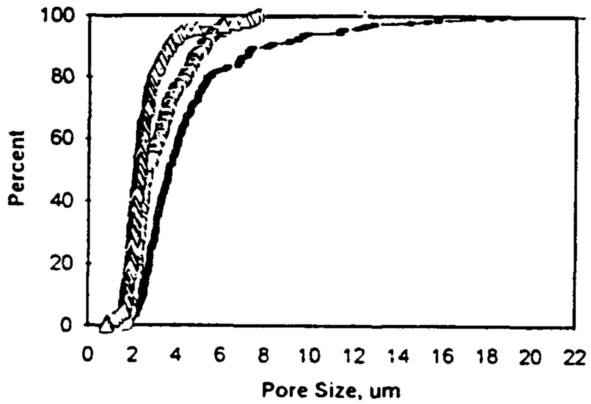


New pedigree, short transverse

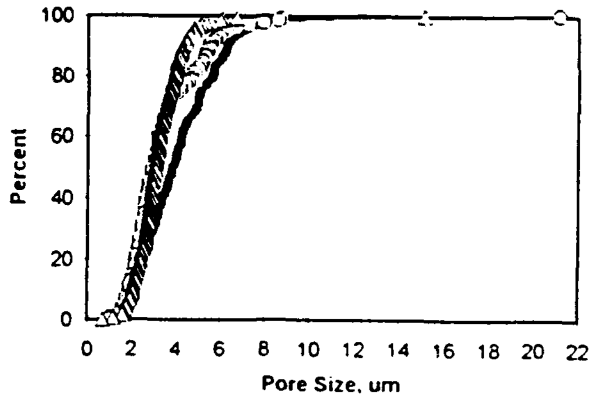


L VECTOR
TS PLANE

Old pedigree, transverse



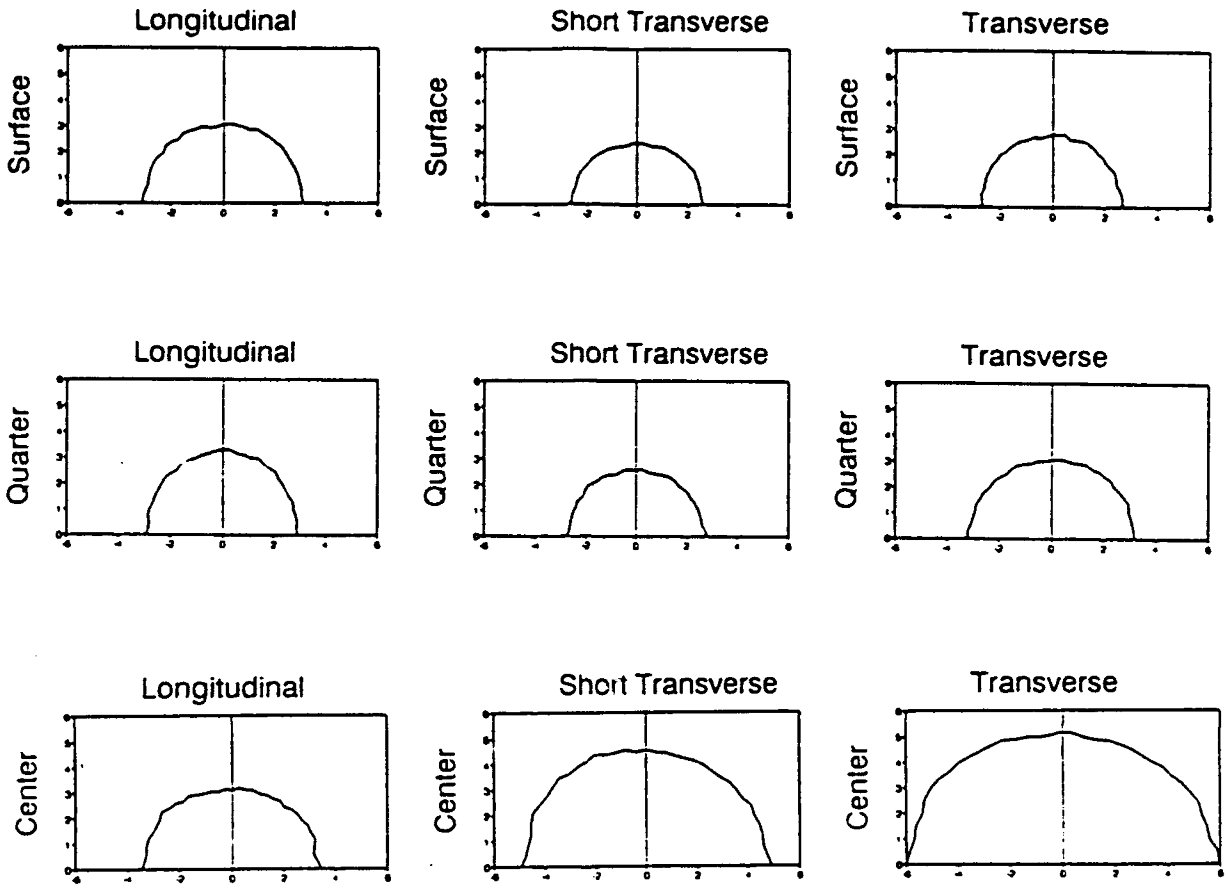
New pedigree, transverse



Ctr Qtr Surf

Ctr Qtr Surf

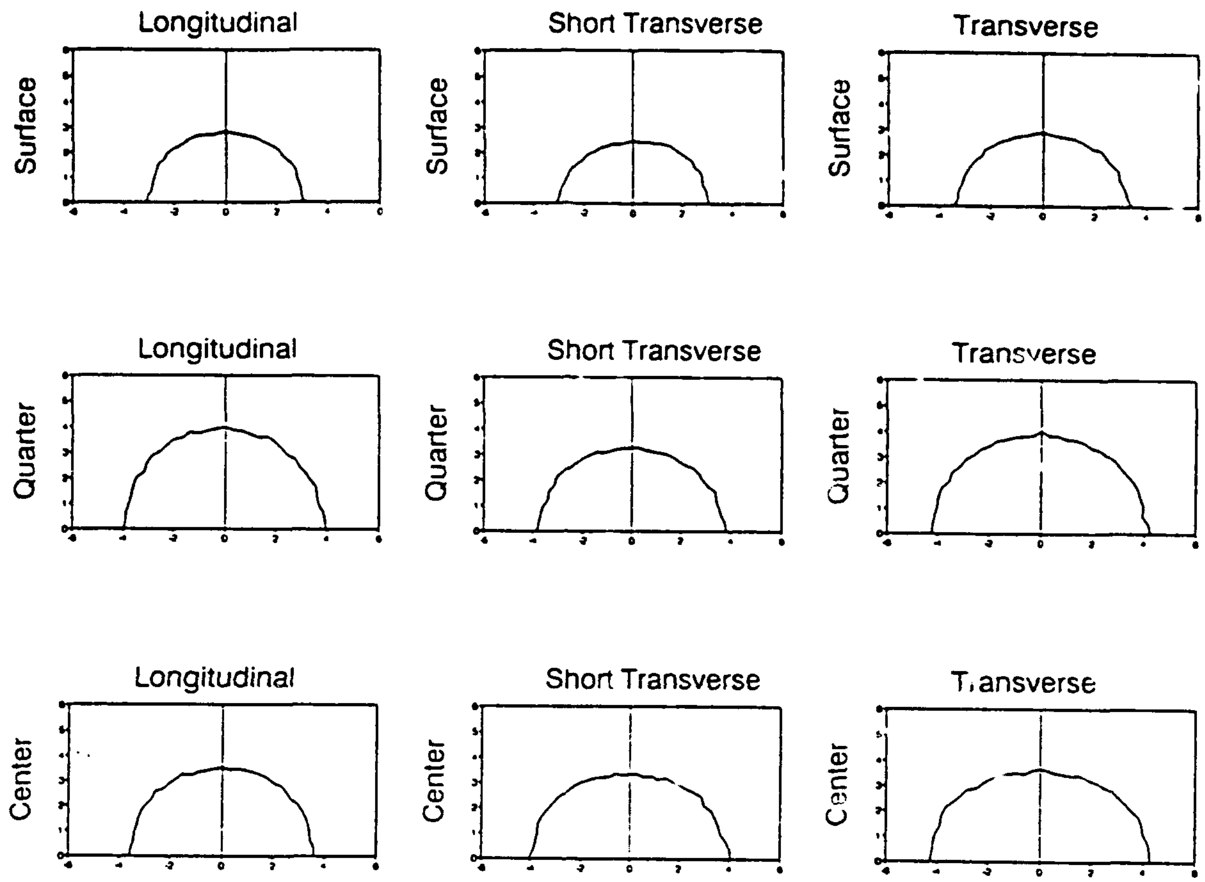
VECTOR S T L
PLANE LT LS TS



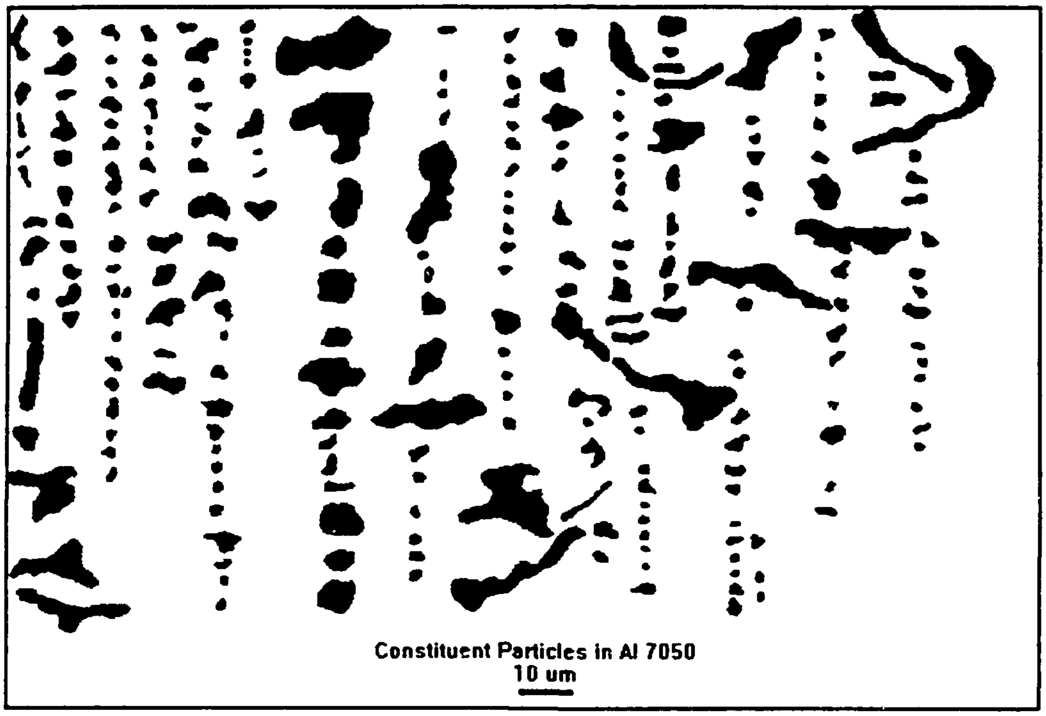
The average sizes of the pores in the old pedigree 7050 Al plate alloy in different directions and orientations. The locations of each section are indicated by the x and y titles and the units used are in micrometers.

VECTOR PLANE

VECTOR	S	T	L
PLANE	LT	LS	TS



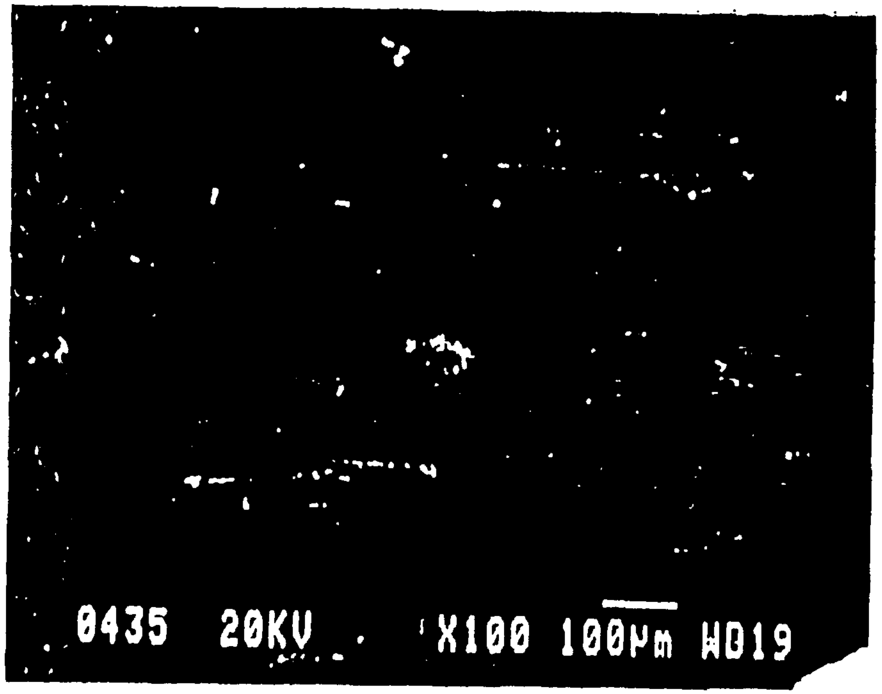
The average sizes of the pores in the new pedigree 7050 Al plate alloy in different directions and orientations. The locations of each section are indicated by the x and y titles and the units used are in micrometers.



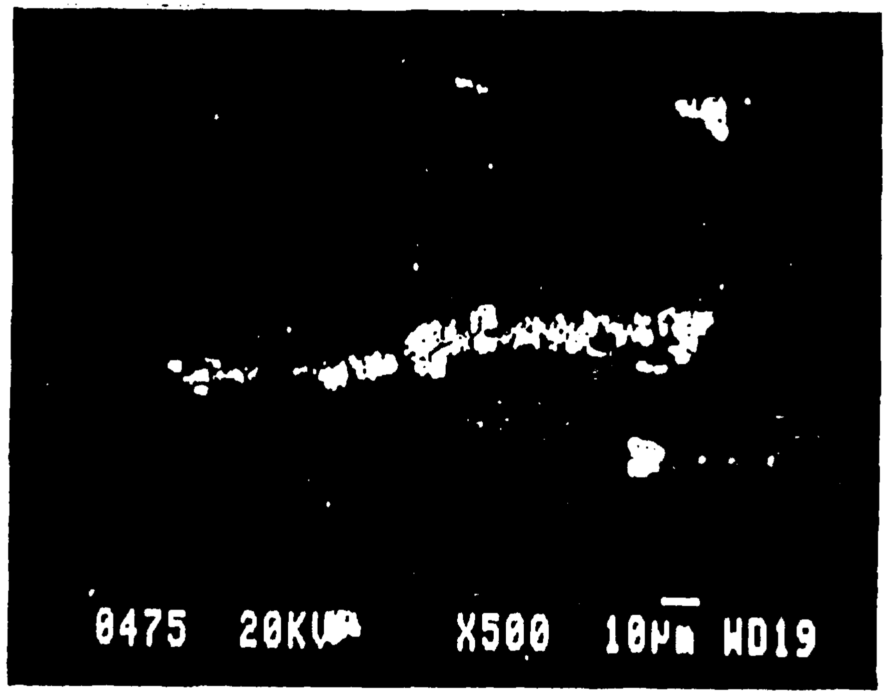
A collection of 236 constituent particles in the old pedigree of the 7050 Al plate alloy. These particles are collected from 60 micrographs.

Microstructural Characterization: Low Porosity Plate

Backscattered SEM images of constituent particles in low porosity plate showing particle clustering



200 μm

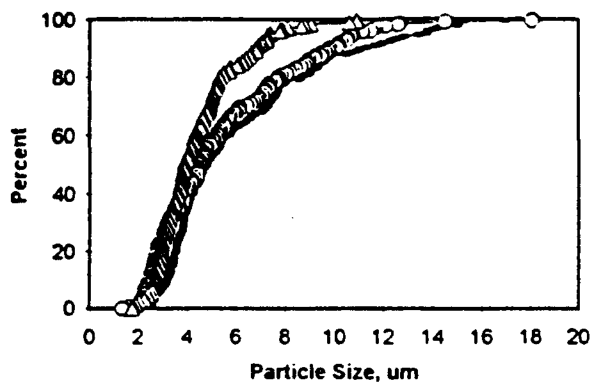


50 μm

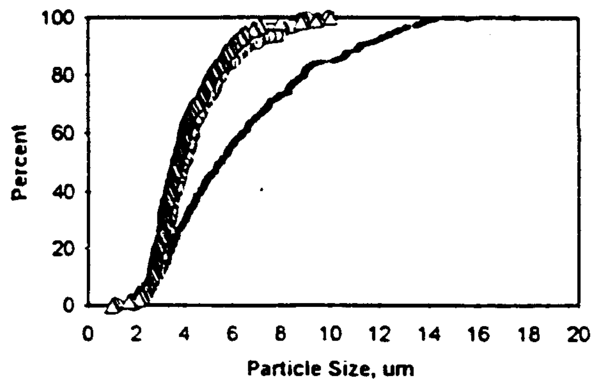
PTCS.XLS

S VECTOR
LT PLANE

Old pedigree, longitudinal

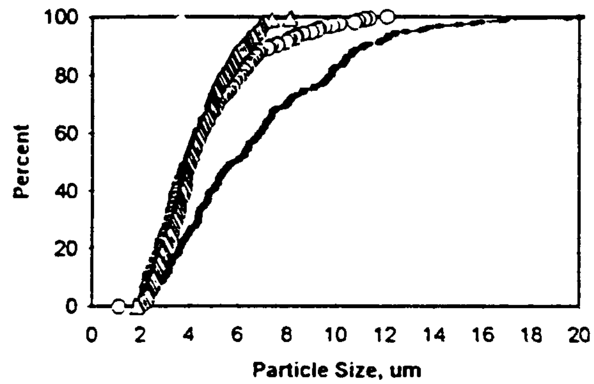


New pedigree, longitudinal

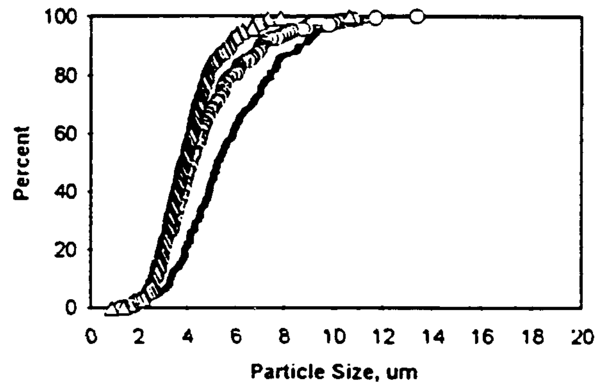


T VECTOR
L-S PLANE

Old pedigree, short transverse

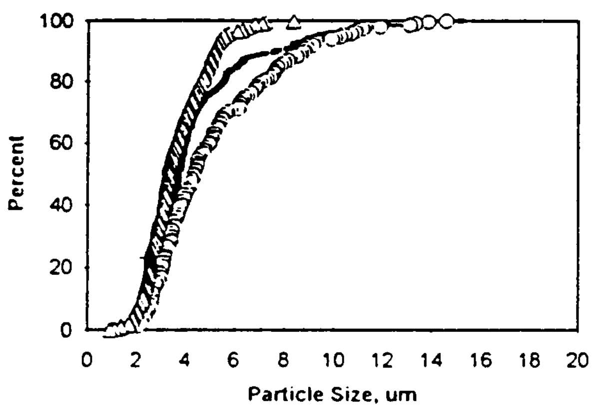


New pedigree, short transverse



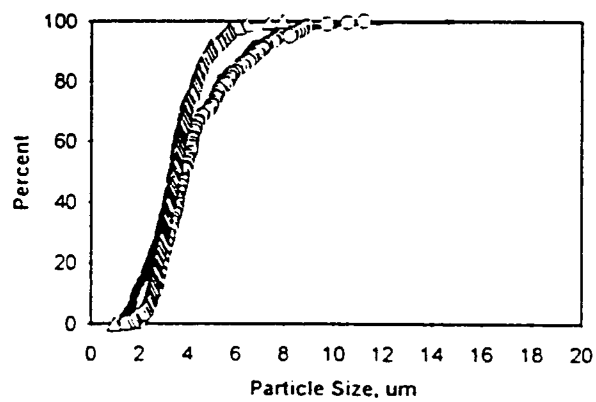
L VECTOR
TS PLANE

Old pedigree, transverse



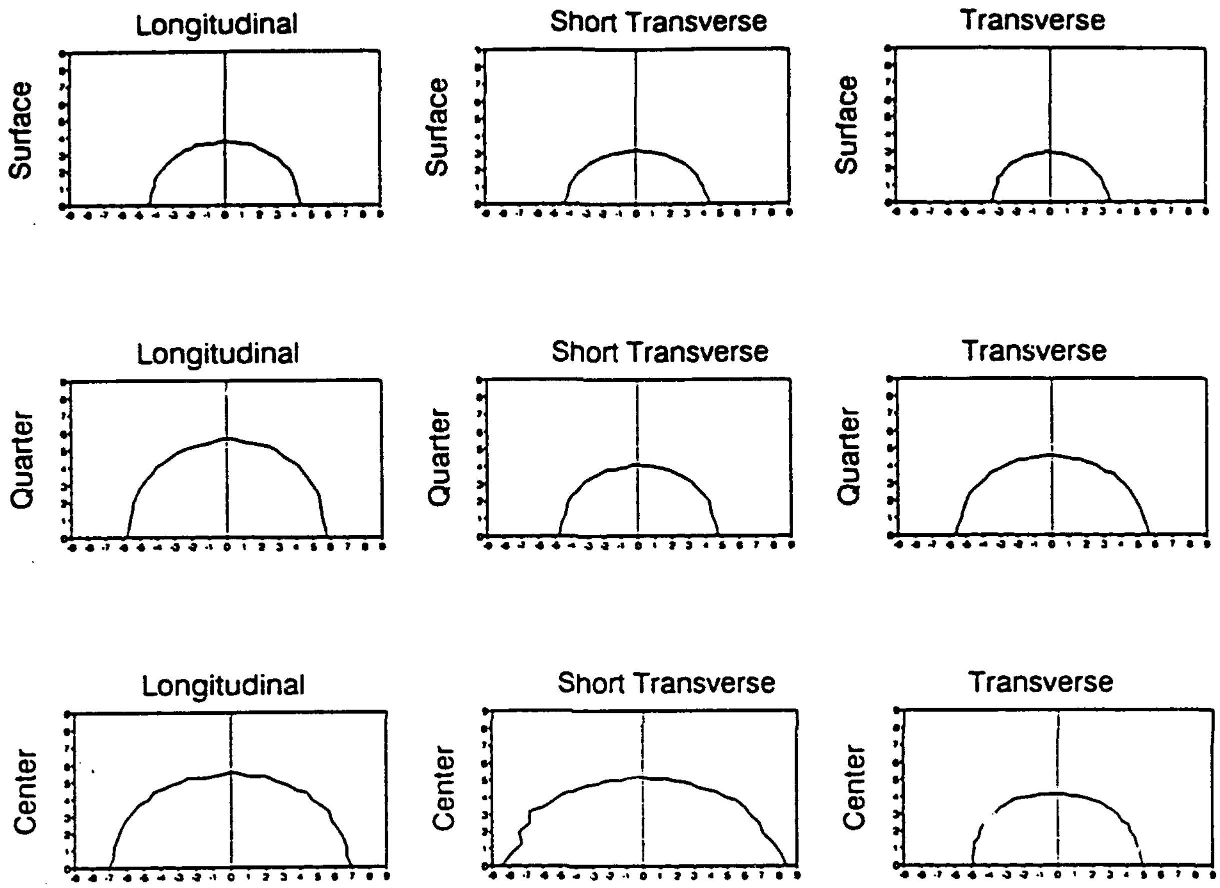
Ctr Qtr Surf

New pedigree, transverse



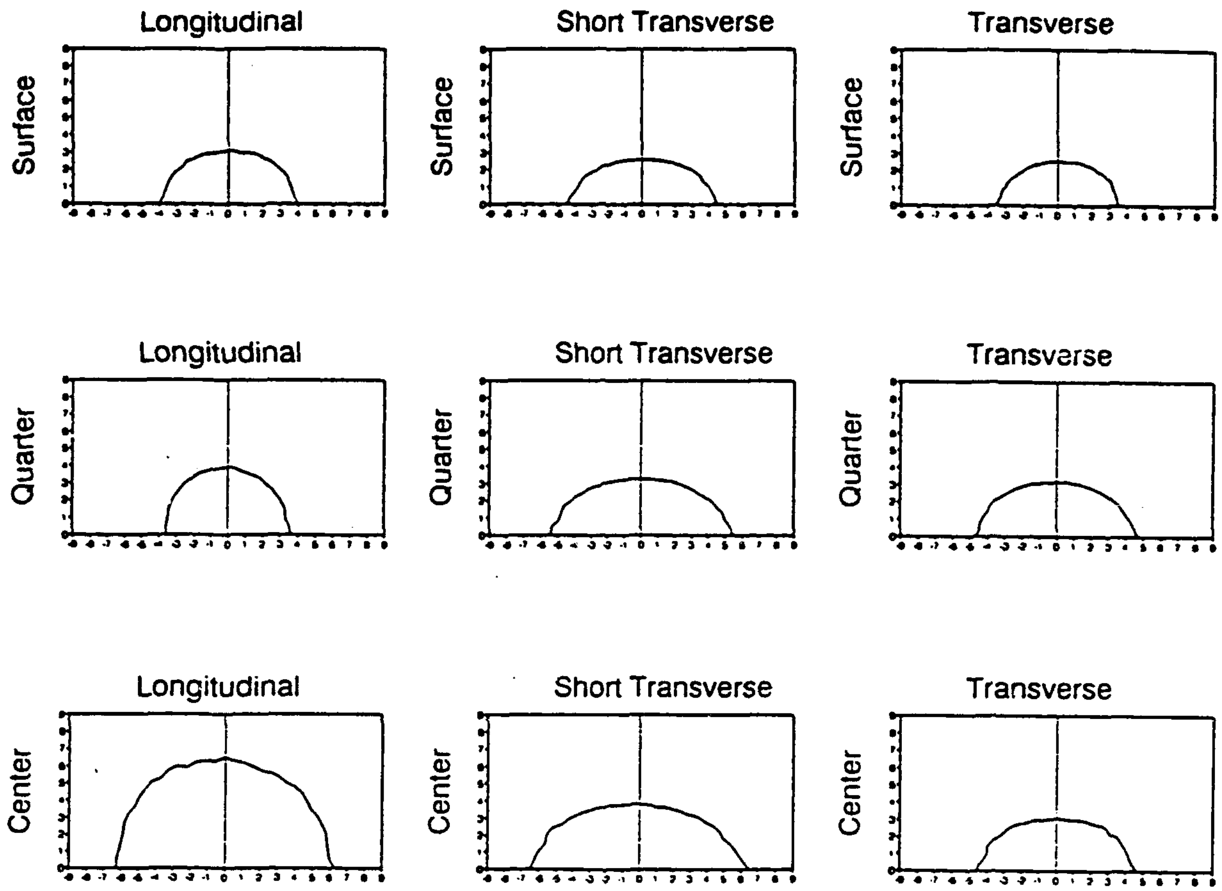
Ctr Qtr Surf

VECTOR S T L
PLANE LT LS TS



The average sizes of the constituent particles in the old pedigree 7050 Al plate alloy at different directions and orientations. The locations of each section are indicated by the x and y titles and the units used are in micrometers.

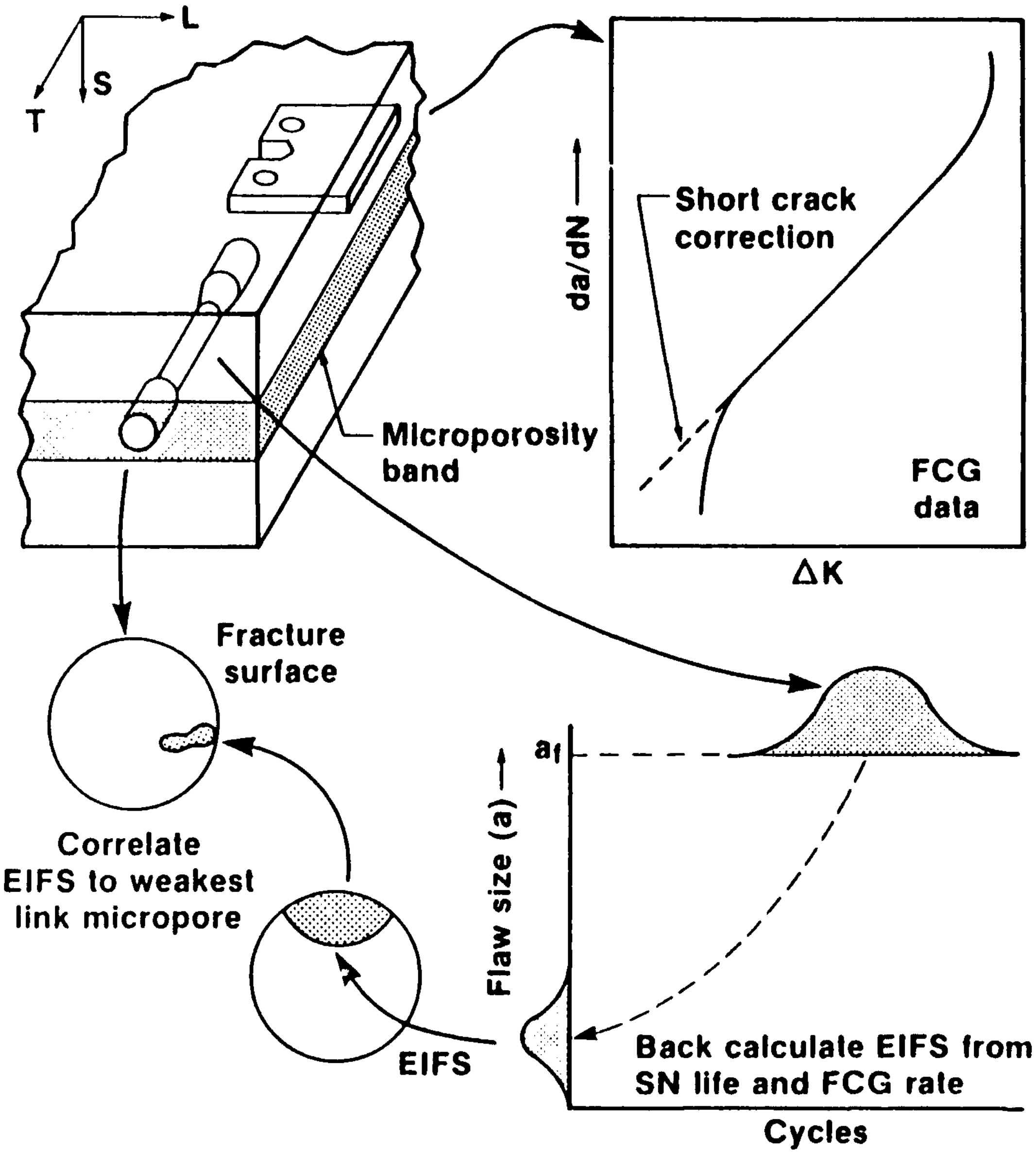
VECTOR	S	T	L
PLANE	LT	LS	TS



The average sizes of the constituent particles in the new pedigree 7050 Al plate alloy in different directions and orientations. The locations of each section are indicated by the x and y titles and the units used are in micrometers.

GA 33475.3

Analytical Approach to Obtaining Material EIFS Distribution



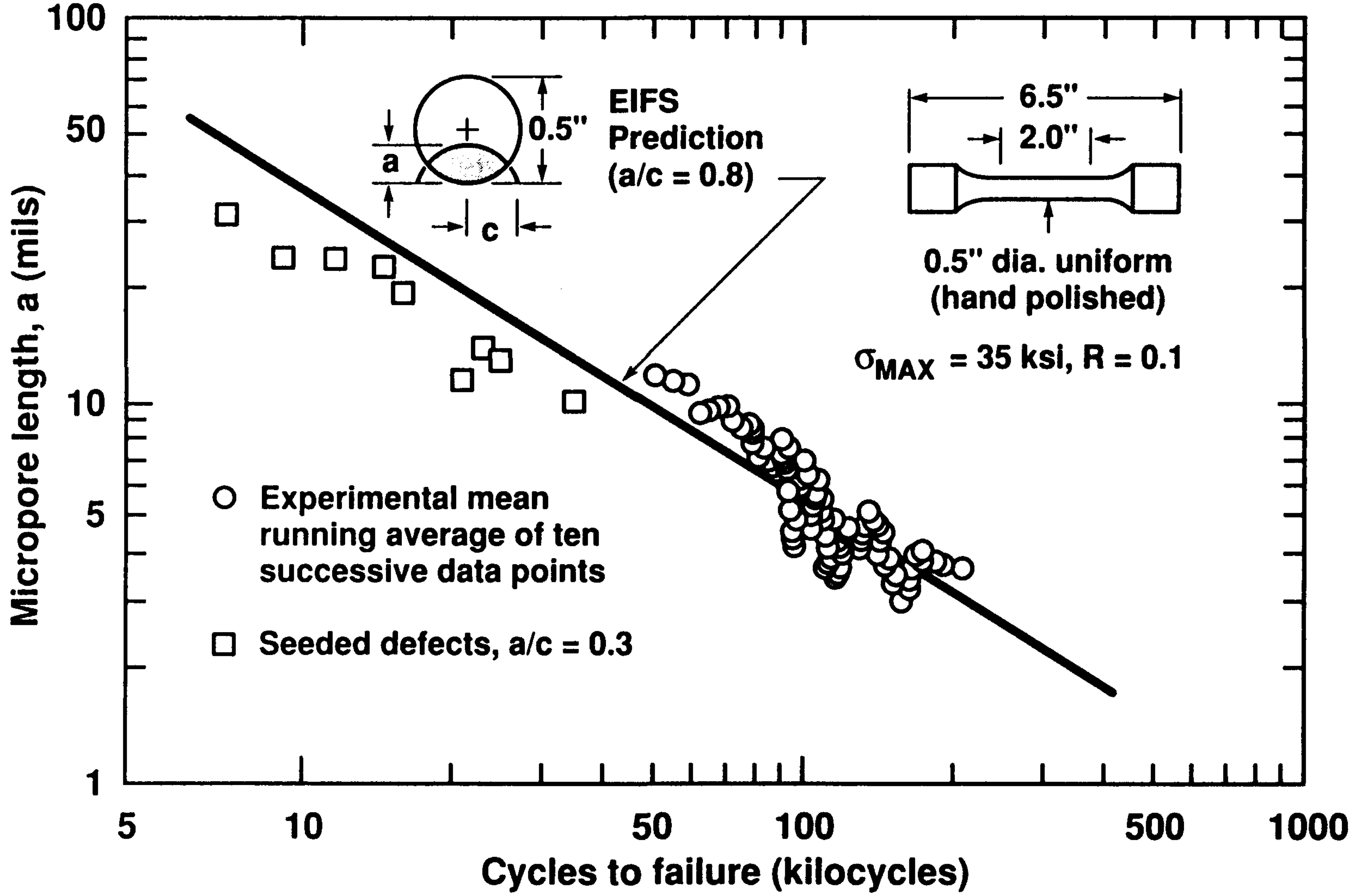
GA-22677.2

Micropore Length vs. Cycles to Failure

7050-T7451 Thick Plate (5.7-5.9 in.)

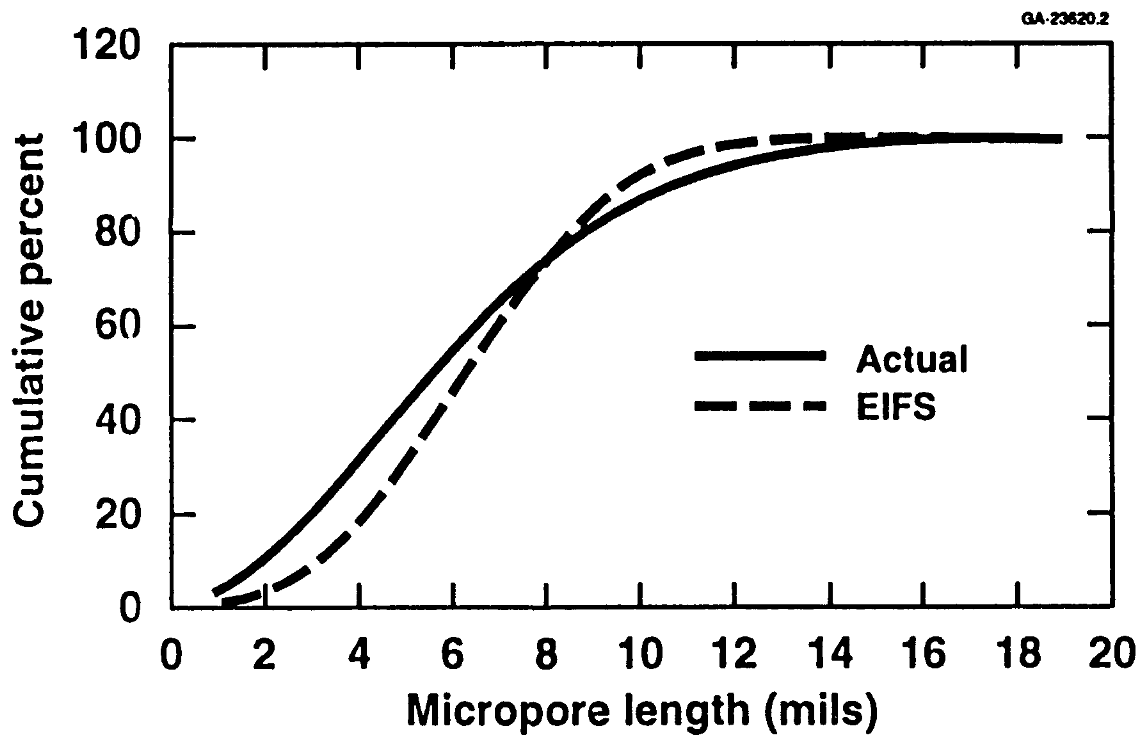
(Long Transverse, T/2 Test Location)

Material Reliability

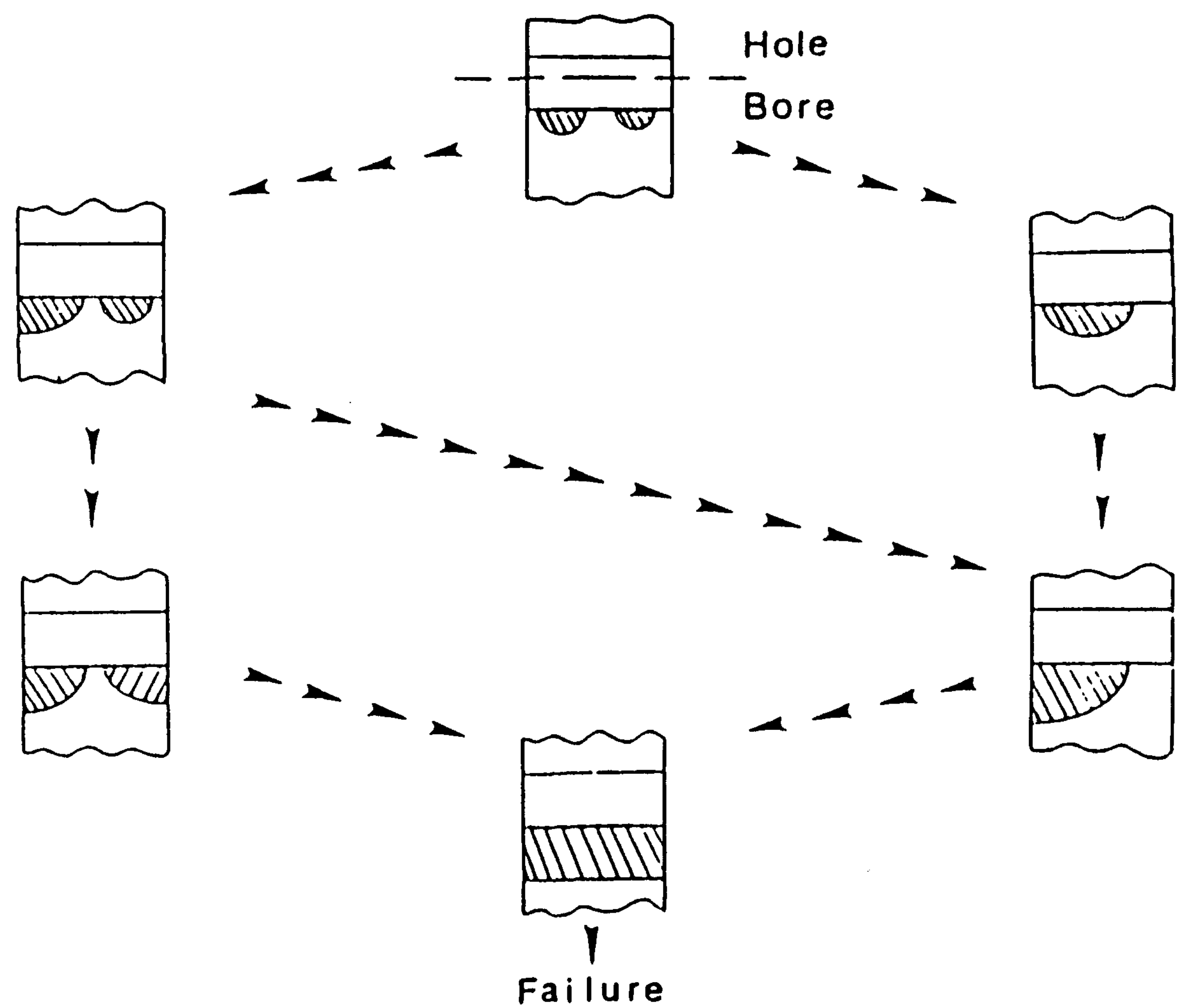


Weibull Distributions of Actual and EIFS Micropore Length

('84 Data)

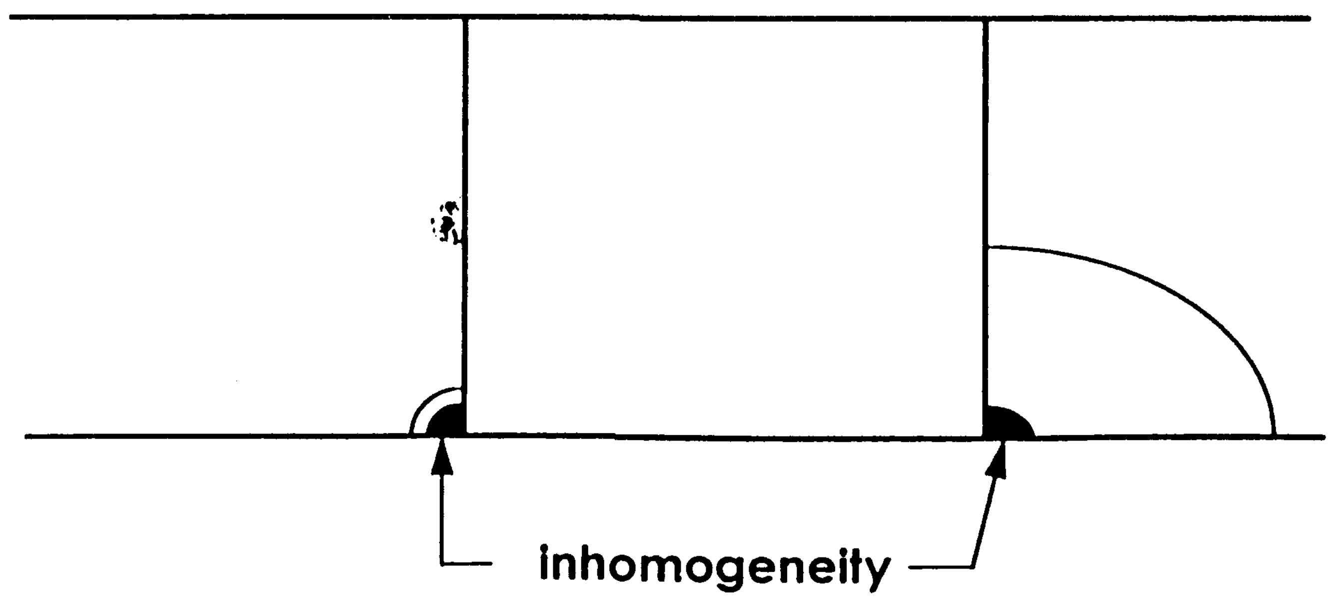


Crack Growth Model

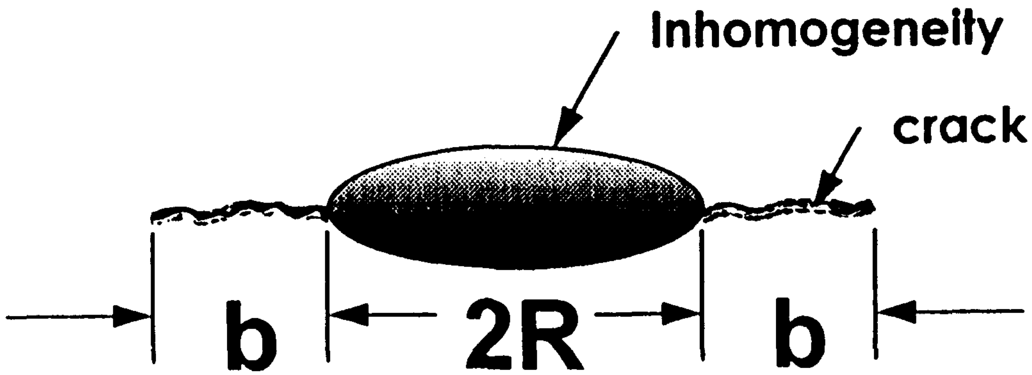


Stress Intensity Factor Solutions

- "Large" Crack
  - Ignore inhomogeneity
  - Newman & Raju solutions
- "Small" Crack
  - Consider inhomogeneity
  - Trantina & Barishpolsky modification



Trantina-Barishpolsky K Solution



$$\boxed{K = \sigma(\pi b)^{1/2}\,\beta}$$

$$\beta = 2/\pi + B(1.12K_t - 2/\pi - 1)(R/(b + R))^{10} + (R/(b+R))^{1.8}$$

B = 1 for void,
= 2.0 for bonded inclusion
= 0.3 for unbonded inclusion

Note: when b >>R, R/(b+R) = 0,
("penny" crack)
when b = 0, R/(b + R) = 1,
(no crack)

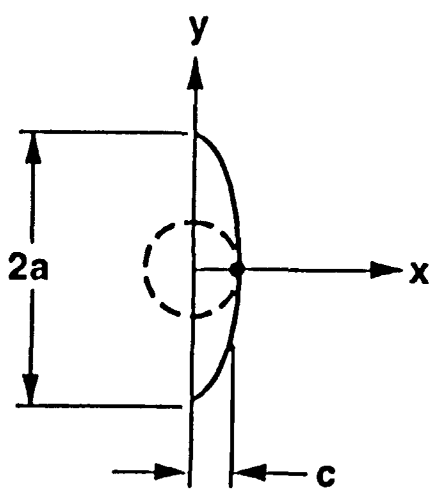
Approximations to Apply Trantina-Barishpolsky K Solution to Surface/Corner Cracks at Hole

- *Move crack to hole bore*

GA 32301.4

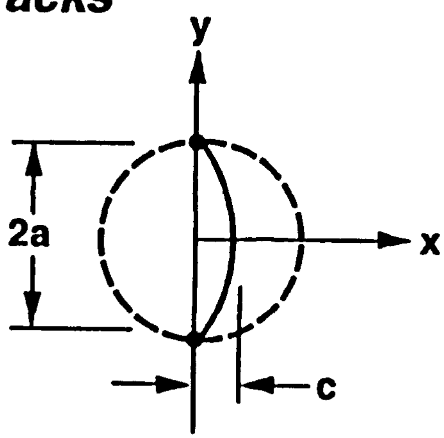
$$K_{effective} = \frac{K_{Trantina}}{K_{Penny}} \times K_{Newman/Raju}$$

- *Noncircular cracks*



- *x-direction*

c = b + R

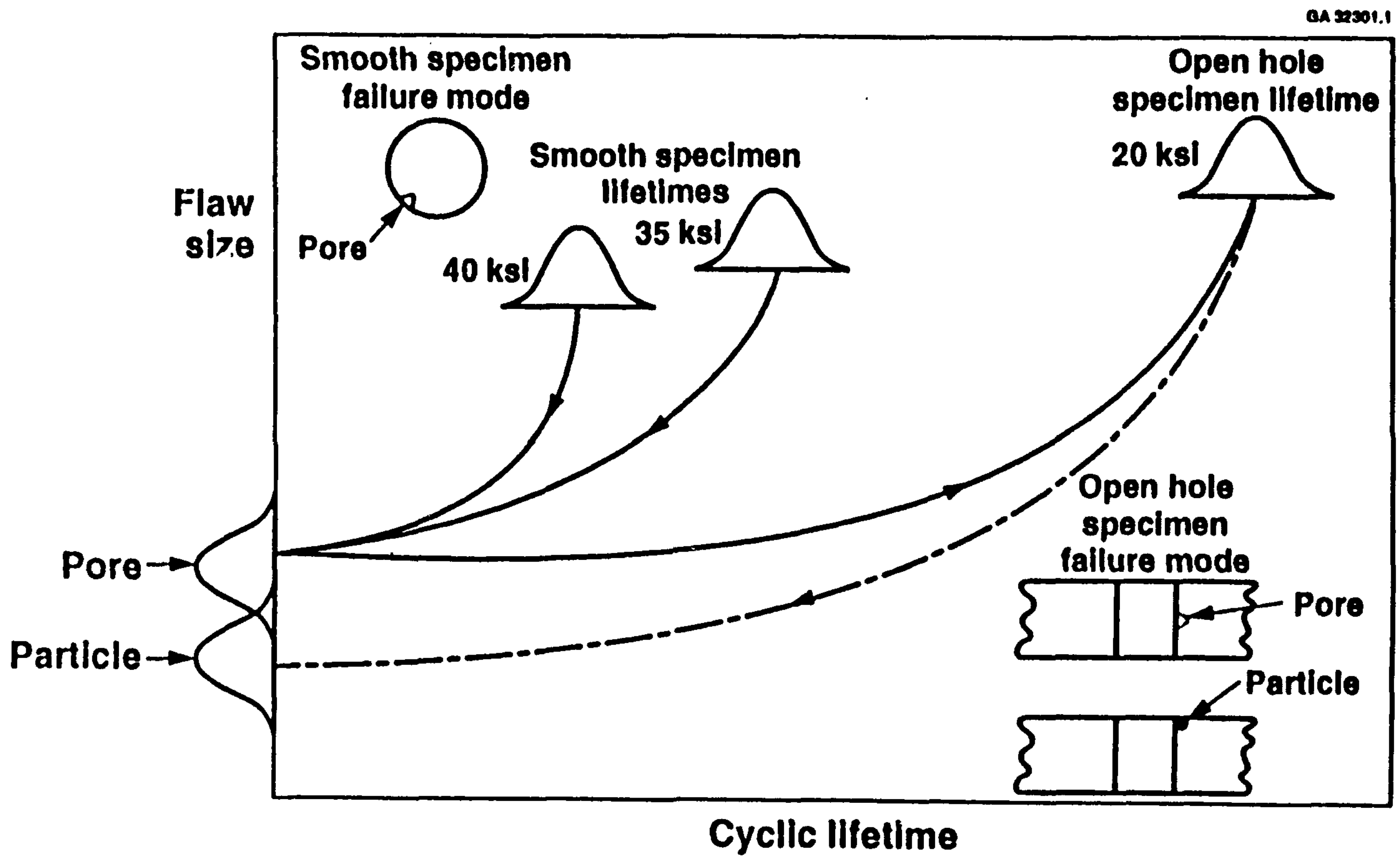


- *y-direction*

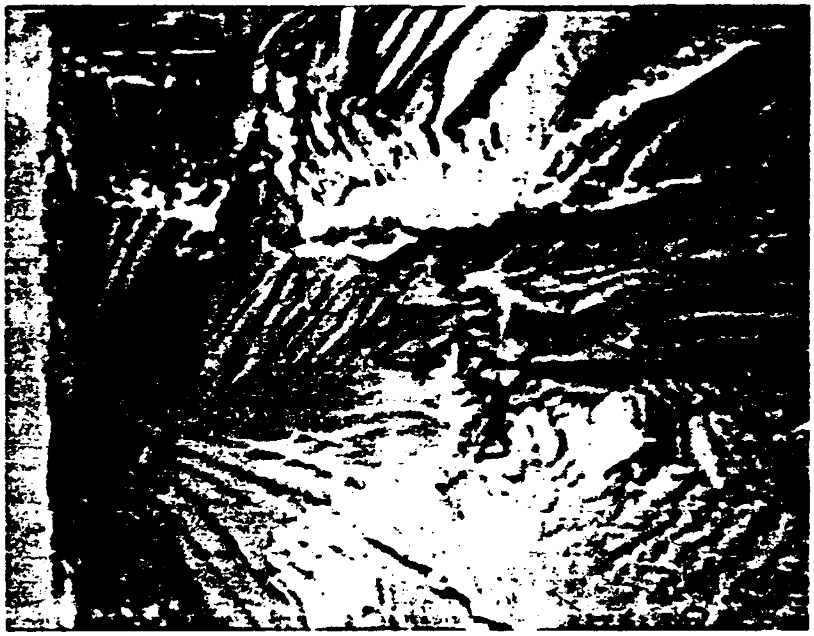
a = b + R

Pore and Particle Distribution Having Equivalent Open Hole Lives

As derived from smooth specimen data



GA 30692 1

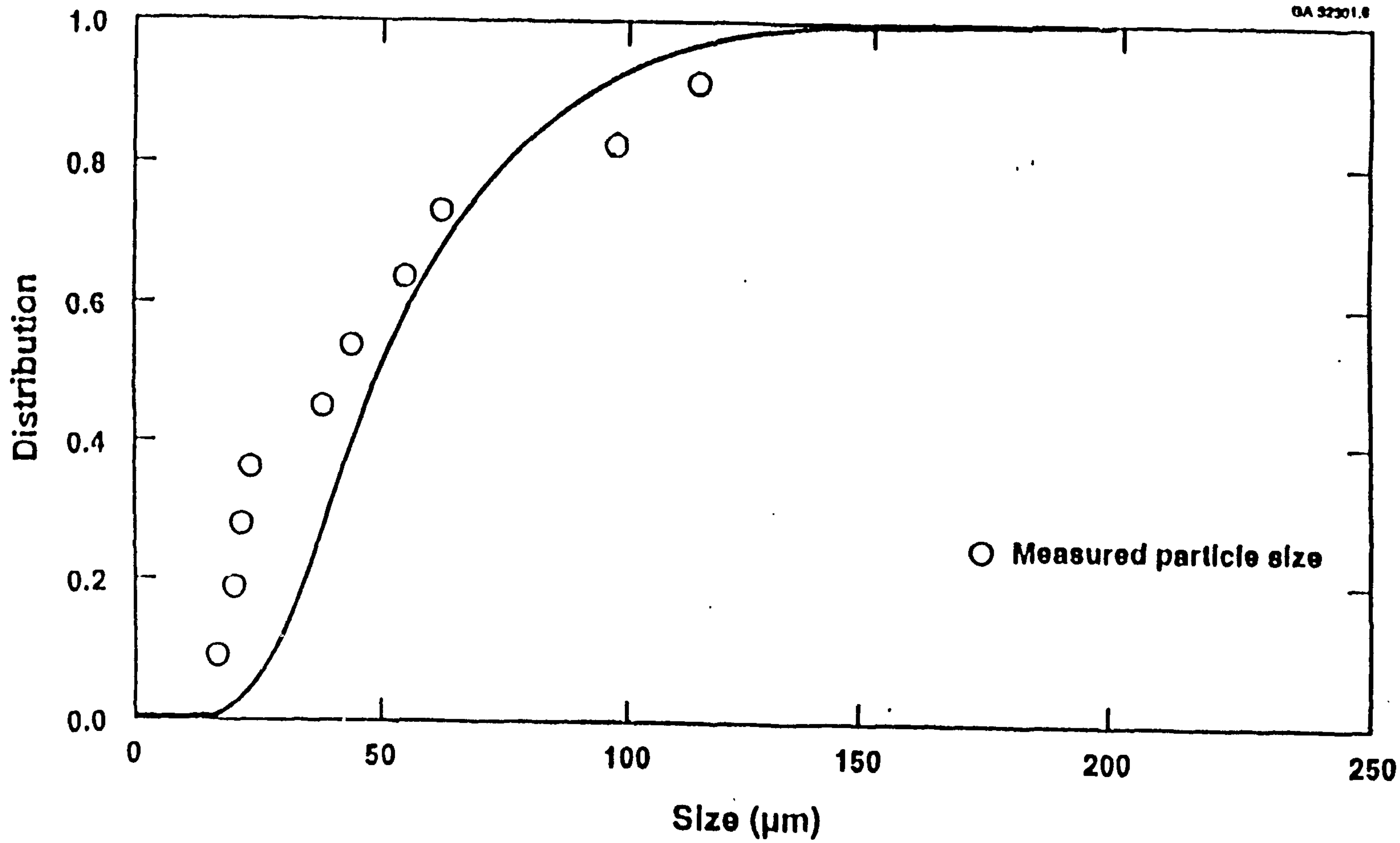


a) Interior porosity of 710 μm^2.
Actual life: 80,700 cycles,
Predicted life: 80,000 cycles.

b) Corner particle of 324 μm^2.
Actual life: 79,500 cycles.
Predicted life: 74,500 cycles.

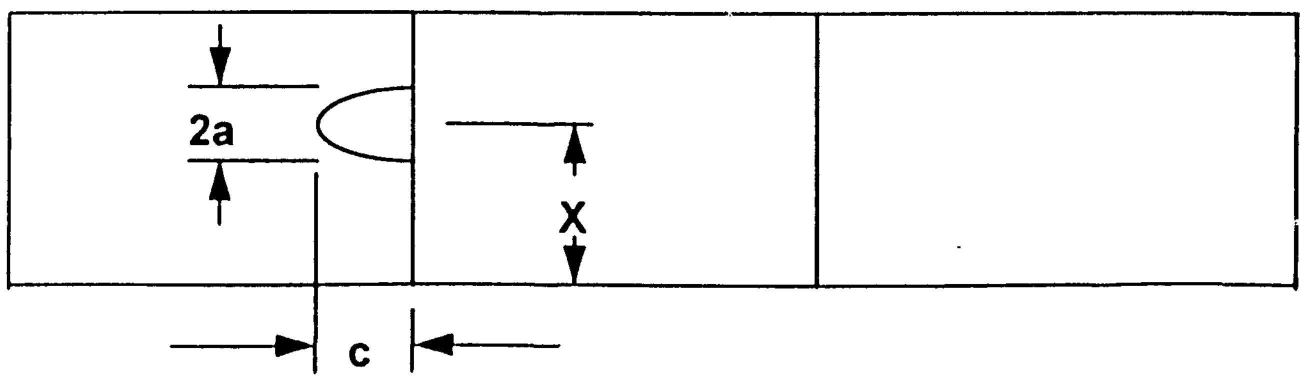
Verification of Trantina-Barishpolsky Analysis for Type of Inhomogeneity
Figure 6

Comparison of the Cumulative Distribution Functions: Equivalent Life Particle and Measured on Low Porosity Plate



Probabilistic Simulation

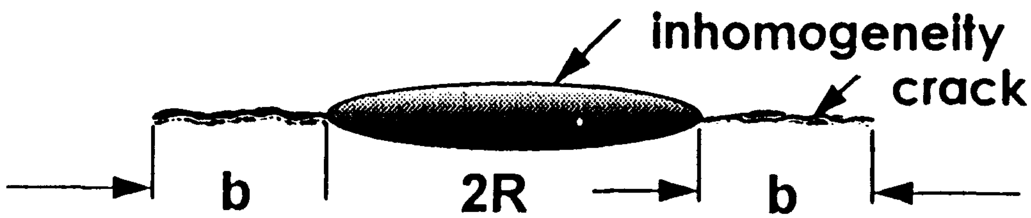
- Crack growth analysis linked to PROBAN
- Stratified Monte Carlo sampling of inhomogeneities
  - Latin Hypercube sampling
  - 100 samples per stress level
- Input micropore distribution
  - Single pore--based on observations
  - x-location
  - a, c dimensions



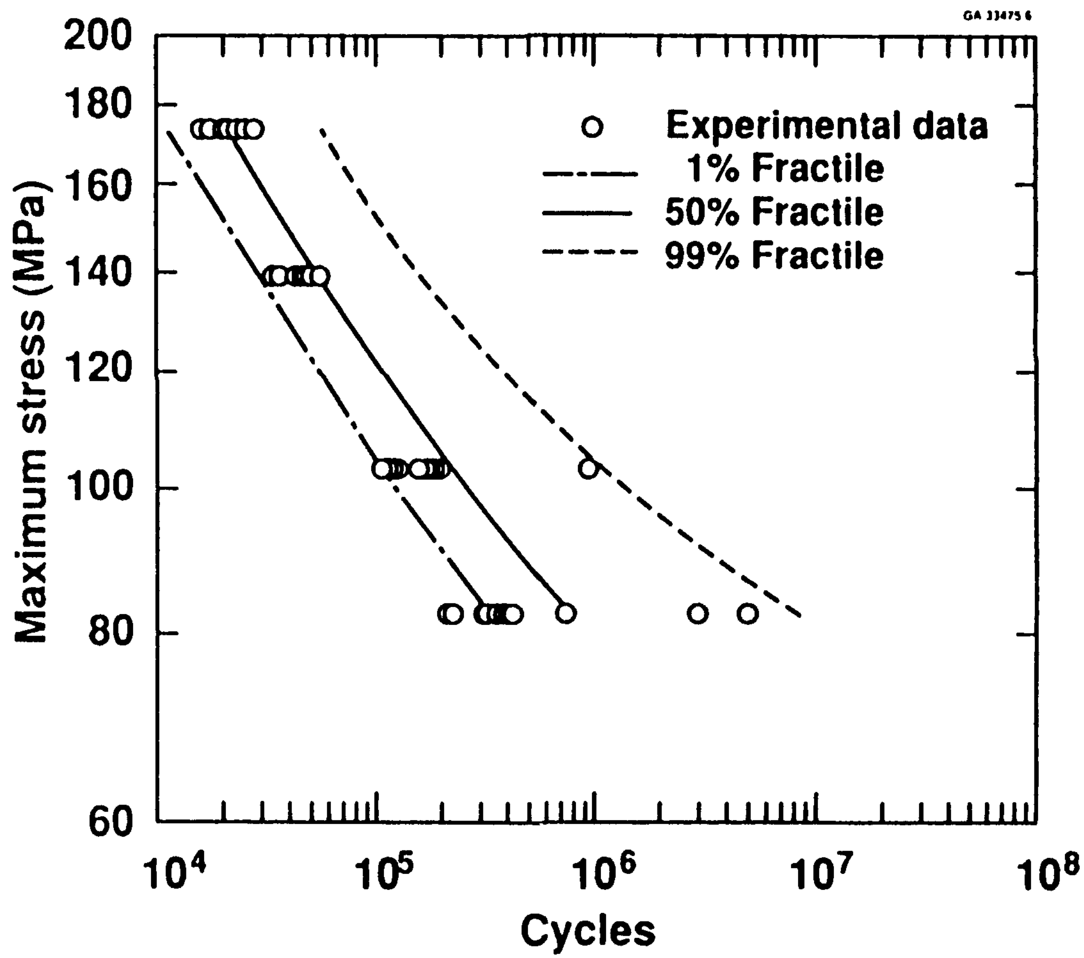
R/(b+R) Parameter

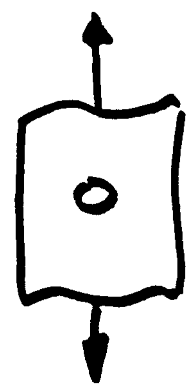
- Measure of "equivalent" initial cracked portion of inhomogeneity
- Compute life for open hole tests with "old" material
  - assume mean micropore dimension
  - vary R/(b+R) to give mean life

R/(b+R) = 1.079 - 0.0011 * stress range



Comparison of Statistical Life Prediction and Experimental Data for Old Quality Material





R/(b+R) Parameter

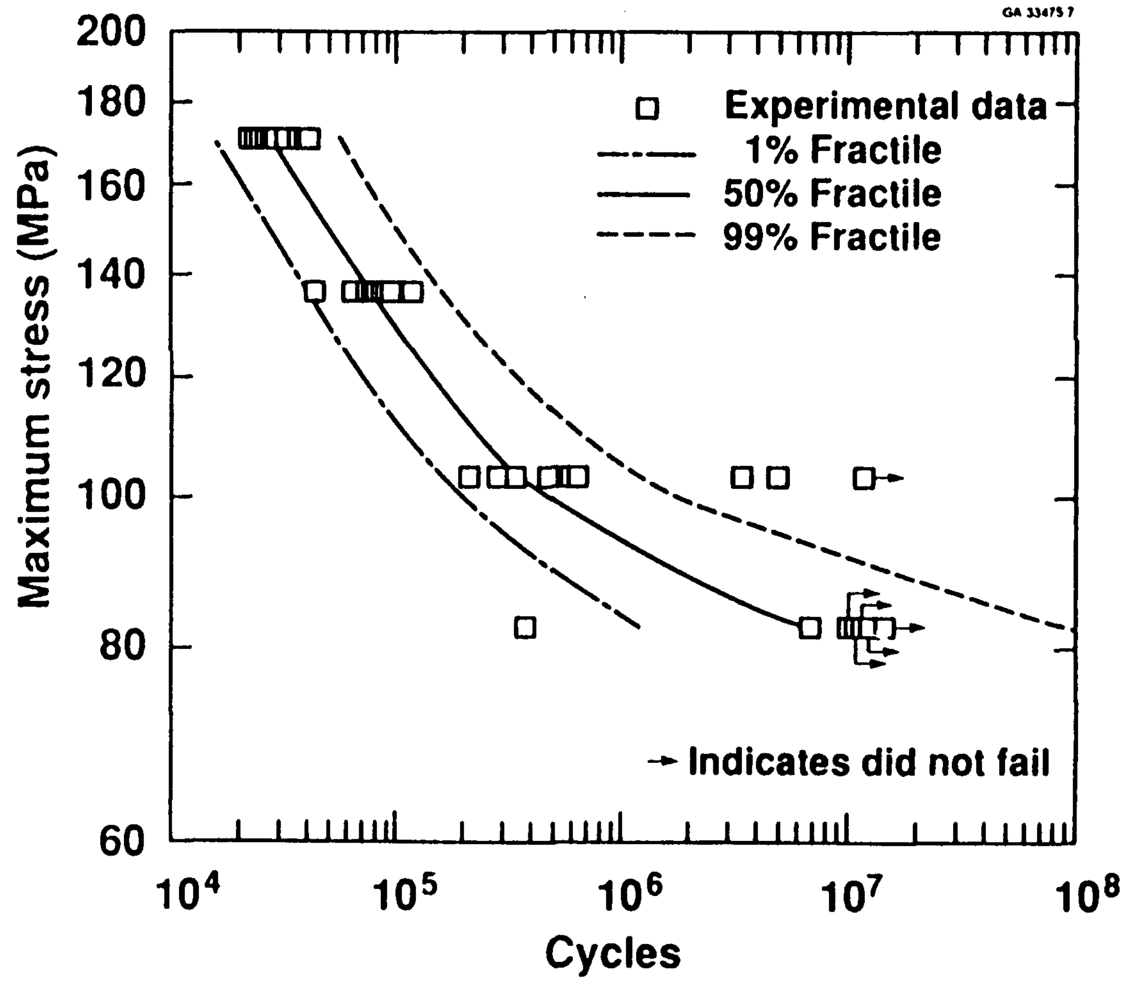
- For other materials, assume same stress dependency, find intercept
  - use mean life at 1 stress level
  - used fatigue limit here

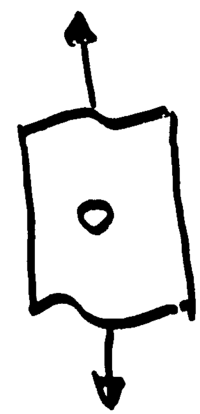
$$\boxed{R/(b+R) = XXXX - 0.0011 * \text{stress range}}$$

- Obtain inhomogeneity distribution from other measurements
- Monte Carlo simulation for entire S-N curve

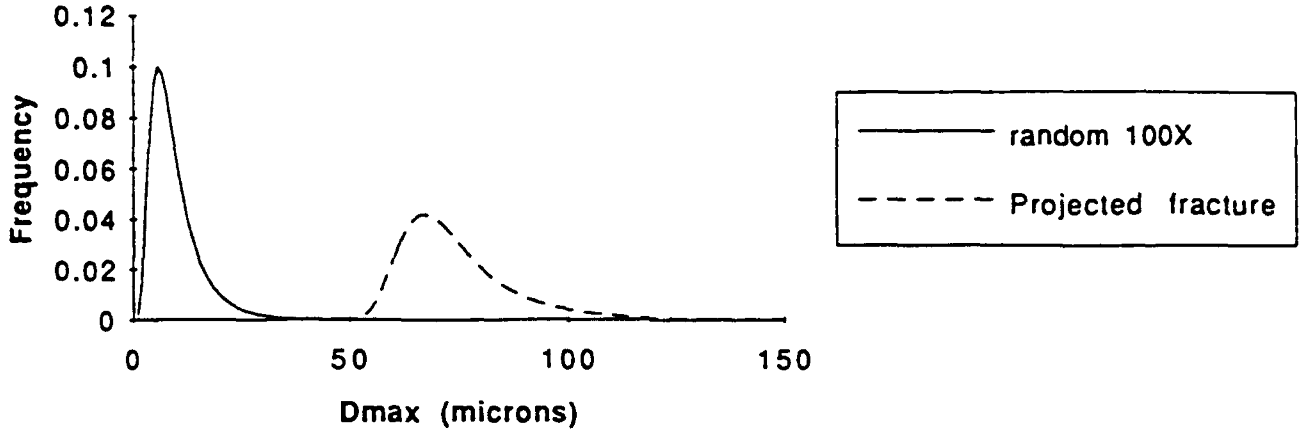
2

Comparison of Statistical Life Prediction and Experimental Data for New Quality Material

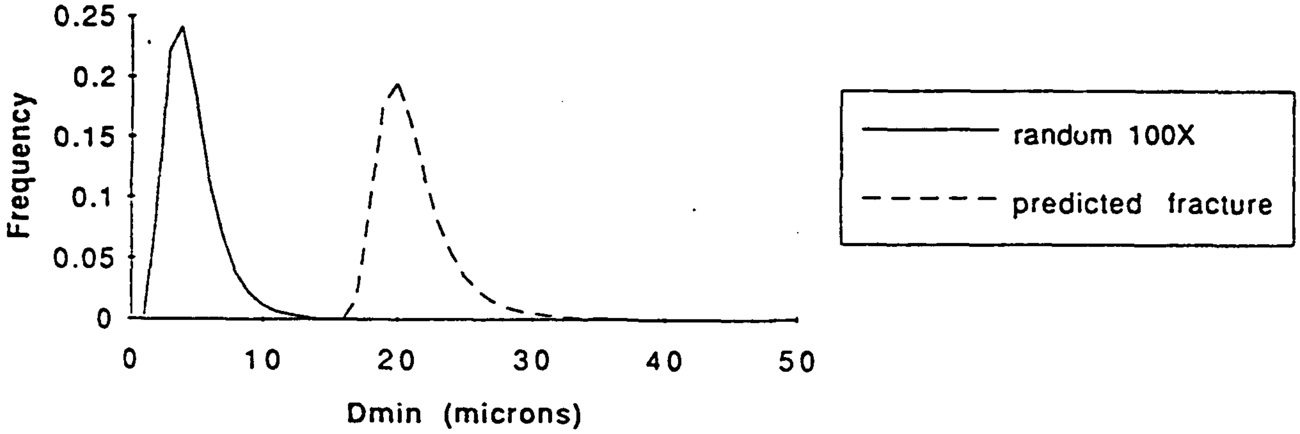




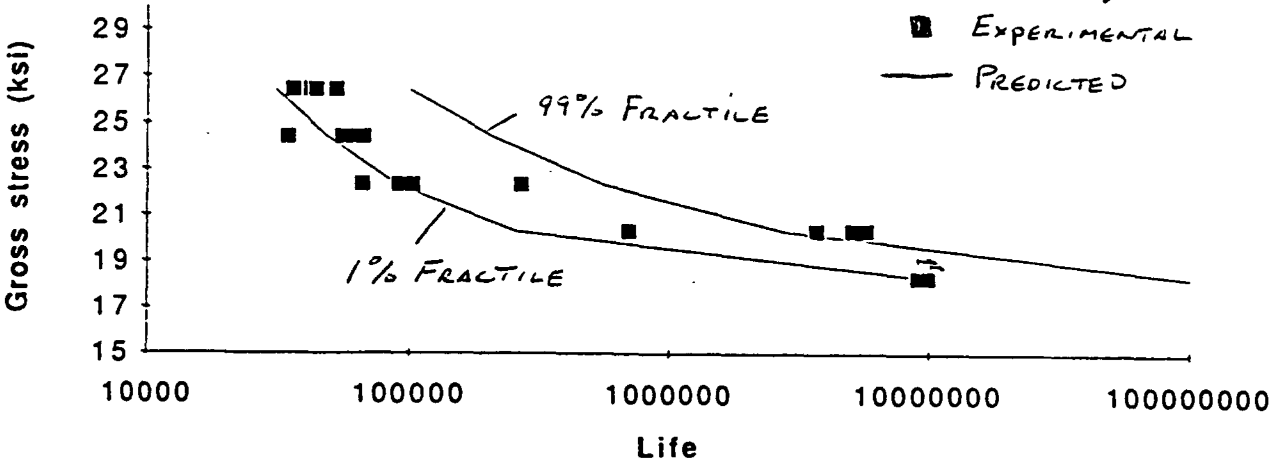
Comparison of Partical Density Functions: Dmax (PARTICLE MAJOR AXIS)
(1 inch Thick 7050 Plate)



Comparison of Partical Density Functions: Dmin (PARTICLE MINOR AXIS)
(1 inch Thick 7050 Plate)

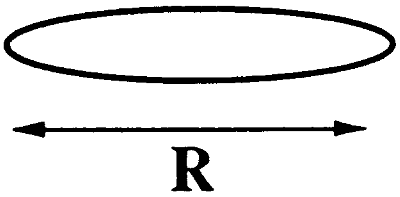


COMPARISON OF PREDICTED AND EXPERIMENTAL RESULTS
(OPEN HOLE SPECIMEN, 1 INCH THICK 7050 PLATE)

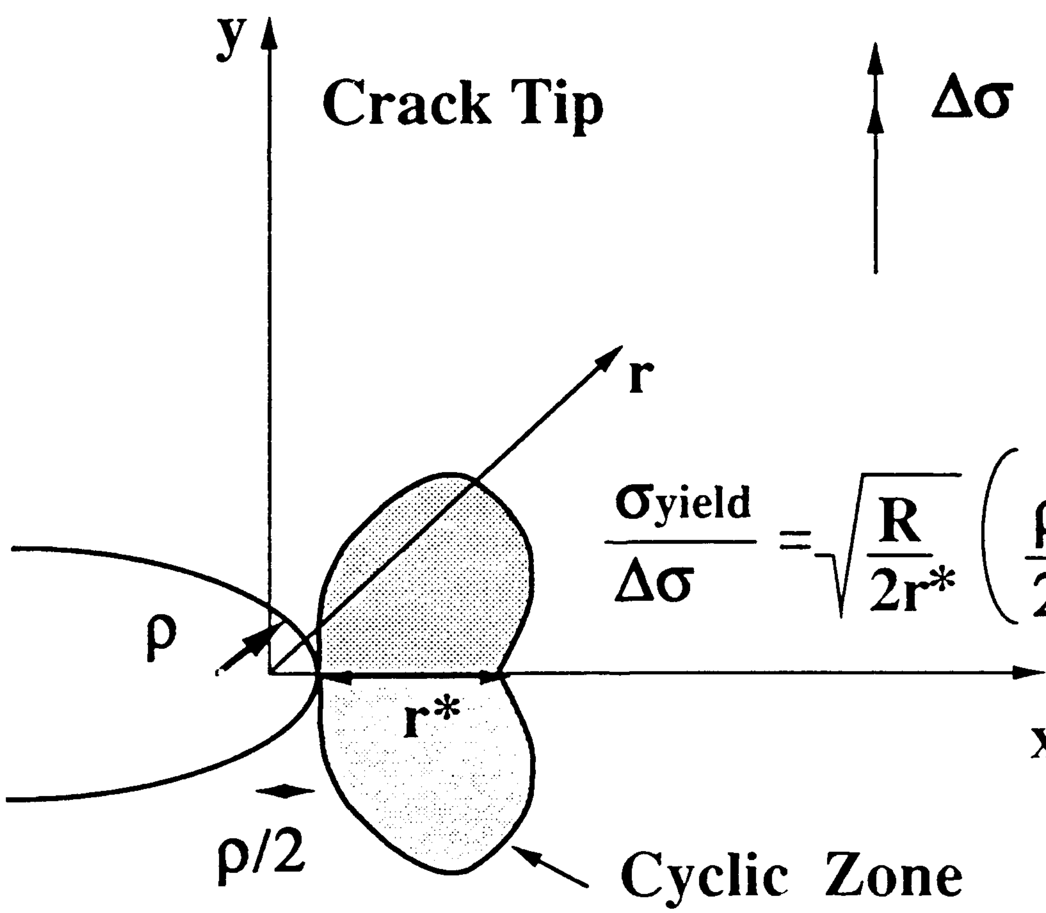


Initiation Model

Inhomogeneity



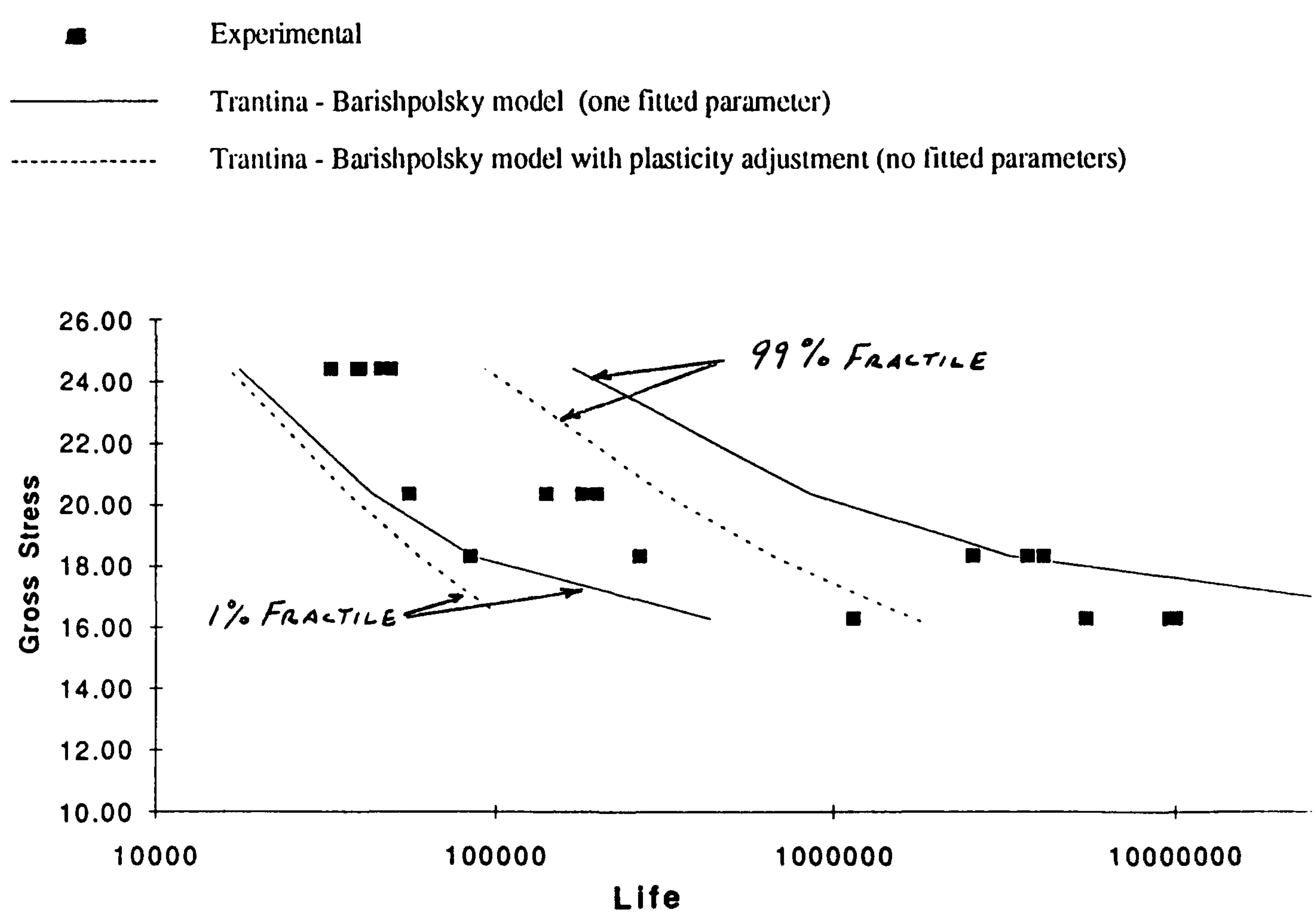
R : Size



$$\frac{\sigma_{yield}}{\Delta\sigma} = \sqrt{\frac{R}{2r^*}}\left(\frac{\rho}{2r^*} + 1\right) + 1$$

$$r^* = f\,(\Delta\sigma \,/\, \sigma_{yield},\ R,\ \rho)$$

Fatigue Life Prediction from Random Plane Microstructure
Open hole specimen, new quality 7050 thick plate



Preliminary Conclusions

Fatigue life prediction modeling
Aluminum 7050-T7451 product variants

- Fracture mechanics concepts shown to apply down to the scale of microstructural features controlling crack initiation in aluminum 7050 thick plate
  - Crack evolution and early growth modeled as a Trantina-Barishpolsky crack relatable to the microstructure
  - Stress intensity factors established for cracks originating from pores and particles in proximity of a free surface or open hole
  - Crack growth rate integration addressed in traditional way
  - Input da/dN-ΔK relationship adjusted for short crack (either by extending power law relationship to low ΔK, or using generated short crack data)
  - Model converges to classical behavior for long cracks
  - Calculation process integrated into general purpose probabilistic soft ware
- The hierarchy of microstructural features (pores/particles) controlling fatigue crack initiation in 7050 product variants have been successfully measured and modeled

Preliminary Conclusions (continued)

Fatigue life prediction modeling
Aluminum 7050-T7451 product variants

- Size distributions of crack initiating microstructural features (extreme value population) can be measured directly by fractography or calculated from either test lives or random plane microstructures

- Initial inhomogeneity populations can be grown forward to predict fatigue life

- Effects of initial inhomogeneity size, shape and location on specimen lifetime distribution modeled

- Hypothetical structural behavior scenarios provided to illustrate the significant performance and cost saving potential of higher quality materials

- Potential shown for large R&D time and cost saving
  - Number of fatigue tests can be appreciably reduced
  - Labor intensive analytical steps (e.g., fractography) can be replaced

Future Work Suggestions

- Fabricate/characterize low particle 7050 thick plate
- Quantification of grain structure effect
  - Original program set out to accomplish this with Al-Li alloy; current work suggests this should be done on alloy 7050
- Scale up technology demonstration program(s)
  - Life assessment methodology
  - New products
  - Thick parts
- Integrate fatigue quality concepts into fatigue/residual strength structural integrity assessment framework (i.e., establish probabilistic criteria)
- Computer aided engineering tools
  - Cost effective exploitation requires computerization to store and manipulate large amounts of information

Technology Demonstration Program
Breakdown by Phase & Description

I. Present concept of thick part fatigue improvement

- Integrate relevant data and needs; use current program data and related experience to demonstrate concept feasibility
- Define program (players, applications, work scope)

II. Provide next generation HFL plate product

- Fabricate product
- Evaluate critical items for success
- Conduct gate review to obtain go-ahead for full concept demonstration

III. Scale to full concept

- Evaluate prototype component(s)
- Project review
- Develop commercial and logistical implementation plans

Budget Summary

• Original contract funding	$788K
• Authorized through 93-12-15	$631K
• Expended through 93-06-30	$441K*

• Authorized funds remaining	$190K

* Includes $130K spent on discontinued Al-Li work